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Aerotherm Report No. UM-70-14

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**USER'S MANUAL
AEROTHERM CHARRING MATERIAL THERMAL
RESPONSE AND ABLATION PROGRAM
VERSION 3**

**Volume I - Program Description
and Sample Problems**

April 1970

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**Air Force Rocket Propulsion Laboratory
Director of Laboratories
Edwards, California 93523
Air Force Systems Command
United States Air Force**

Project Officer, Robert J. Schoner/RPMCH

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Volume I - Program Description
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Prepared Under
the Sponsorship of

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FOREWORD

This report is one of two computer program user's manuals prepared by Aerotherm Corporation under USAF Contract F04611-70-C-0012. Included herein is Volume I of the manual for Version 3 of the Aerotherm Charring Material Ablation code. This volume describes the problems solved by the code and presents an input (card format) user's guide and sample problems. The report was first published as Aerotherm Report No. UM-70-14. The work was administered under the direction of the Air Force Rocket Propulsion Laboratory, Motor Component Development Branch with Mr. R. J. Schoner as project officer.

Mr. M. R. Wool was program manager and principal investigator. Significant additional assistance was also provided by Dr. C. B. Moyer.

This technical report has been reviewed and is approved.

R. J. Schoner
Project Engineer, AFRPL

ABSTRACT

This two-volume report describes a Fortran IV computer code which computes the transient thermal and ablation response of a charring insulation material structure. The program is for one-dimensional bodies, but can treat a variety of shapes, including planes, cylinders, spheres, and more general thermal "stream tube" bodies. The program can treat complex systems including a main ablating material, several charring back-up materials, and a multiple non-charring material back-up structure.

An unusual feature of the code is the very general heated surface boundary condition, which can account for

- Simple specified temperature and recession rate
- Specified heat flux with no recession
- General thermochemical erosion model incorporating complete chemical erosion computations, both equilibrium and non-equilibrium, for any material exposed to any environment

The code has seen extensive use for thermal performance studies of ablating heat shields, rocket nozzles, and spacecraft structures.

Volume I of this report contains descriptions of the problem treated, the equations solved, the input information required of the program user, and the program output information. It also provides a card-by-card user's input guide and a number of sample problem input and output listings. Volume II of the report contains supplemental information on the specific Fortran IV codings. It includes program listings, flow charts, and definitions of Fortran variable names.

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LIST OF SYMBOLS

GENERAL

A	area	ft ²
A	coefficient in Equation (8) for T_w	Btu/ft ² sec F
A_{BW}	area of back wall of ablating material	ft ²
A_s	area of surface of ablating material	ft ²
a	radius exponent giving variation of area with radius, $A \sim r^a$	---
B	coefficient in Equation (8) for T_w	Btu/ft ² sec
B_i	pre-exponential factor, Equation (2)	sec ⁻¹
B'	$\dot{m}/\rho_e u_e C_M = (\dot{m}_g + \dot{m}_c)/\rho_e u_e C_M$	---
B'_f	dimensionless ablative mass flow rate of failing (melting or mechanically removed) material, $\dot{m}_f/\rho_e u_e C_M$	---
B'_g	dimensionless pyrolysis gas rate $\dot{m}_g/\rho_e u_e C_M$	---
b	constant in burning rate equation, Section 2.3.4	various
C_H	Stanton number corrected for transpiration (blowing) $C_H/C_{H_0} = \zeta/(e^\zeta - 1)$ and for radius ratio effects	---
C_{H_0}	Stanton number not corrected for transpiration (blowing) or for radius ratio effects, i.e., as input	---
C_{H_1}	Stanton number corrected for radius ratio effects but not for blowing	---
C_M	mass transfer Stanton number	---
C_p	specific heat	Btu/lb ^o F
E_a	activation energy, Equation (2)	Btu/lb mol
F	view factor	---
F_i	empirical function of temperature	---
$f_1(x), f_2(x)$	functions of plastic mass fraction x, discussed in Section 2.1	---
H	recovery enthalpy	Btu/lb
h	enthalpy (sensible plus chemical)	Btu/lb
h^T	enthalpy of formation at temperature T	Btu/lb

h_c	convective transfer coefficient	Btu/ft ² sec ^{°F}
h_g	pyrolysis gas enthalpy	Btu/lb
\bar{h}	defined as $(\rho_p h_p - \rho_c h_c)/(\rho_p - \rho_c)$	Btu/lb
K	proportionality constant in Equation (21)	---
K_i	mass fraction of species i in a mixture	---
k	thermal conductivity	Btu/ft-°F-sec
\dot{m}	mass flow rate per unit area from surface	lb/ft ² sec
\dot{m}_g	mass flow rate of pyrolysis gases out of surface per unit surface area	lb/ft ² sec
\dot{m}_{gx}	local in-depth mass flow rate of pyrolysis gases through node or control volume	lb/sec
n	burning rate exponent, Equation (17)	---
p_c	chamber pressure	lb/ft ²
q_{chem}	chemical energy rate term defined by Equation (11)	Btu/ft ² sec
q_{cond}	rate of energy conduction into the ablating material	Btu/ft ² sec
$q_{rad\ in}$	rate of radiant energy input to the ablating surface	Btu/ft ² sec
$q_{rad\ out}$	rate of radiant energy emission from the ablating surface, equal to $F\sigma\epsilon T_w^4$	Btu/ft ² sec
q_{sen}	convective flux term defined by Equation (10)	Btu/ft ² sec
R	universal gas constant	Btu/lb mol °R
r	radius	ft
r^*	throat radius	ft
\dot{r}	propellant burning rate	ft/sec
r_c, r_p	char and pyrolysis density criteria	---
r_s	radius of heated surface	ft
S	distance from original location of receding surface to current surface location	ft
\dot{S}	rate of change of S	ft/sec
T	temperature	°R
T'	"new" temperature computed during a computational cycle	°R
T_w	wall (surface) temperature	°R

u_e	velocity of gases at edge of boundary layer	ft/sec
x	coordinate normal to ablating surface, fixed to receding surface, also virgin plastic mass fraction defined by Equation (5)	ft, ---
y	coordinate normal to ablating surface, origin fixed in space relative to back wall	ft
Z_i	diffusion driving force = $\frac{K_i}{P_i \sum_j \frac{K_j}{P_j}}$	---
Z_i^*	modified Z_i discussed in Reference 2	---
GREEK		
α	thermal diffusivity $k/\rho C_p$	ft ² /sec
Γ	volume fraction of resin in plastic, see Equation (1)	ft ³ /resin/ ft ³ material
δ	nodal thickness, char and pyrolysis line depths	ft
ϵ	emissivity	---
ϵ_p	volume fraction of undecomposed plastic in given volume	---
ζ	$2\lambda\dot{m}/\rho_e u_e C_{H_0}$	---
θ	time	sec
λ	blowing reduction parameter; see ζ and C_H	---
ρ	density	lb/ft ³
ρC_p	defined as $[\epsilon_p \rho_p C_{p_p} + (1 - \epsilon_p) \rho_c C_{p_c}]$	Btu/ft ³ °R
ρ_o	initial density	lb/ft ³ resin or lb/ft ³ rein- forcement
ρ_r	residual density in charred material	lb/ft ³ resin or lb/ft ³ rein- forcement
σ	Stefan-Boltzmann constant	Btu/ft ² sec °R ⁴
τ	char thickness	ft
ψ_i	decomposition reaction order for i^{th} component Equation (2)	---
SUBSCRIPTS		
A	denotes one pyrolyzing component of resin	
B	denotes second pyrolyzing component of resin	

C denotes reinforcement
 c denotes char, also see h_c , p_c
 e denotes outer edge of boundary layer
 f denotes failing (removed by melting or mechanical action)
 g denotes pyrolysis gas
 i,j species indexes
 inj denotes material injected into the boundary layer in gas form
 n nodal index
 NL last node of ablating material
 o see C_{H_2O}
 o original, initial
 p denotes virgin plastic, denotes "in absence of swell"
 r denotes recovery enthalpy; denotes residual density
 s denotes sensible enthalpy; also denotes "at heated surface"
 swell denotes "with swelling effect"
 w denotes wall (heated surface)
 x see \dot{m}_{g_x}
 1,2 see f_1 , f_2 , C_{H_1} , also nodal index
 1,3 denote Options 1 and 3

SECTION 1

INTRODUCTION AND GENERAL PROGRAM DESCRIPTION

1.1 PURPOSE OF THIS DOCUMENT

This report is Volume I of a two volume user's description of the Aerotherm Charring Material Thermal Response and Ablation computer program, Version 3 (CMA). It has as its chief goals the description of the preparation of the necessary input data for the program and the specification of various operational details of the program such as array sizes and tape numbers used. As supplementary information, this volume includes a very brief description of the computations performed. This description is not intended to be complete, but merely serves to give the user some feel for the calculations as well as a better understanding of the input requirements.

Users interested in a more complete description of the program itself are referred to Reference 1. An earlier version of this program is described in detail in Reference 2. This user's manual pertains specifically to what will be termed Version 3 of the CMA code. It differs from the earlier Version 2 edition described in Reference 3 chiefly in the added capability to treat charring back-up materials. Hence, an alternate designation (CMA/CBM or CBM) is used occasionally in this manual.

Volume II of this user's manual contains detailed information about Fortran IV codings. These include Definitions of Fortran variables, Flow Charts of Fortran routines, and Listings of Fortran routines.

1.2 GENERAL DESCRIPTION OF THE CMA PROGRAM

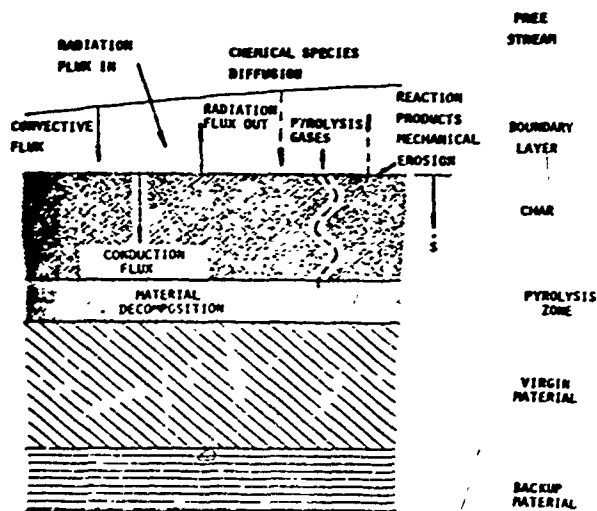
The Charring Material Thermal Response and Ablation Program, Version 3, is an implicit, finite-difference computational procedure for computing the one-dimensional transient transport of thermal energy in a three-dimensional isotropic material which can ablate from a front surface and which can decompose in-depth. Decomposition reactions are based on a three component model. The program permits up to eight different back-up materials of arbitrary thickness, five of which may char. The back wall of the composite material may transfer energy by convection and radiation.

The ablating-surface boundary condition may take one of three forms:

- Option 1 - General convection-radiation heating with coupled mass transfer, using a transfer coefficient approach, including the effects of unequal heat and mass transfer coefficients (non-unity Lewis number) and unequal mass diffusion coefficients. Surface thermochemistry computations need not presume chemical equilibrium at the surface, but can account for kinetic effects, and can also consider thin layer melting or failing.
- Option 2 - Specified surface temperature and surface recession rate.
- Option 3 - Specified radiation view factor and incident radiation flux, as functions of time, for a stationary surface.

Any combination of options may be used for a single computation. Option 3 is appropriate to cooldown after termination of convective heat input and is often useful in conjunction with Options 1 and 2.

The following sketch illustrates the general physical problem treated by the CMA code.



As the material is heated, the original virgin material (or rather one or more components of the original composite virgin material) pyrolyzes and yields a pyrolysis gas, which percolates away from the pyrolysis zone, and a porous residue, which for most materials of interest is a carbonaceous char, possibly reinforced with refractory fibers or cloth.

Superimposed on this basic problem may be a number of even more complex events. The pyrolysis gases percolating through the char may undergo further chemical reactions among themselves, and may react with the char, either eroding it or depositing additional residue upon it ("coking"). The char itself may collapse or fragment from mechanical or thermal stresses, and the refractory reinforcements may melt or suffer mechanical damage. Finally, various constituents of the residue structure may react chemically with each other, changing the nature of the char, and various mechanical forces may remove material from the surface.

Despite these complexities, it is found that the "simple physics" described by

virgin plastic + char + gas

underlies a wide range of problems of technical interest, and for a great many materials, such as carbon phenolic, graphite phenolic, and wood, constitute all the events of interest. Such events as coking, mechanical erosion, melting, and subsurface reactions (other than pyrolysis) are less common and generally characterize specific problems.

The CMA Code, Version 3, treats the basic pyrolysis or charring event for a main insulation material. This material may be backed-up by a number of charring back-up materials, which in turn may be backed-up by noncharring structural elements. The CMA code will treat cracking or fissuring of the char, as well as surface mechanical removal or melting of the char structure.

SECTION 2

PROGRAM FEATURES, CAPABILITIES, AND COMPUTATIONAL PROCEDURES

2.1 IN-DEPTH SOLUTION ASPECTS

The in-depth solution procedure is the controlling feature of the code and accounts for most of the computing time. This procedure is basically a transient heat conduction calculation which is coupled to a pyrolysis rate calculation (and to boundary conditions discussed in Section 2.4 below). The following subsections discuss important aspects of the in-depth solution.

2.1.1 Decomposition (Pyrolysis or Charring)

Since many decomposing char forming materials appear to behave as three independently pyrolyzing components, the program uses a three-component decomposition model for the main material and for any decomposing back-up material.

The resin filler is presumed to consist of two components which decompose separately, while the reinforcing material is the third component which can decompose. The instantaneous density of the composite is given by

$$\rho = \Gamma(\rho_A + \rho_B) + (1 - \Gamma)\rho_C \quad (1)$$

where A and B represent components of the resin, and C represents the reinforcing material, Γ is the volume fraction of resin and is an input quantity (Section 3.1.2). Separate Γ values may be entered for any decomposing back-ups. Each of the three components can decompose following the relation

$$\left. \frac{\partial \rho_i}{\partial \theta} \right|_y = -B_i \exp^{-E_{a_i}/RT} \rho_{o_i} \left(\frac{\rho_i - \rho_{r_i}}{\rho_{o_i}} \right) \quad (2)$$

where ρ_{r_i} is the residual or terminal density of component i , and ρ_{o_i} is the original density of component i . The values ρ_{o_i} , ρ_{r_i} , B_i , ψ_i , and E_{a_i} are input parameters for $i = A, B, C$ for the main material. A separate $i = A, B, C$ set of pyrolysis data may be entered for each decomposing back-up.

The decomposition event is computed explicitly. That is, "old" temperatures are used in Equation (2) to compute the decomposition rates and the new nodal densities.

2.1.2 In-Depth Energy Balance

For the purpose of writing the in-depth energy balance differential equation, we introduce the x coordinate system tied to the receding surface, as shown in the following sketch. In this system, we have the energy equation of the form

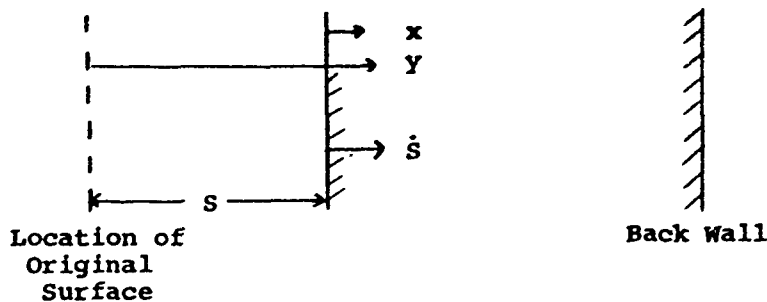
$$\rho C_p \frac{\partial T}{\partial \theta} \bigg|_x = \frac{1}{A} \frac{\partial}{\partial x} \left(kA \frac{\partial T}{\partial x} \right)_{\theta} + (h_g - \bar{h}) \frac{\partial \rho}{\partial \theta} \bigg|_y + \dot{s} \rho C_p \frac{\partial T}{\partial x} \bigg|_{\theta} + \frac{\dot{m}_g}{A} \frac{\partial h_g}{\partial x} \bigg|_{\theta} \quad (3)$$

in which the individual terms have physical meanings which may be interpreted as follows (from left to right): rate of storage of sensible energy, net rate of thermal conduction, pyrolysis energy rate, convection rate of sensible energy due to coordinate system movement, and net rate of energy convected with pyrolysis gas passing a point.

In this equation, the local specific heat and thermal conductivity are formulated from input temperature functions for both virgin plastic and char, C_{pp} , C_{pc} , k_p , and k_c (see Section 3.1.7 below). In partially pyrolyzed zones ($\rho_c < \rho < \rho_p$), the specific heat is formulated with a special mixing rule

$$C_p = x C_{pp} + (1 - x) C_{pc} \quad (4)$$

where the weighting variable x is based on the convenient fiction that partially pyrolyzed material is a simple mixture of pure virgin plastic and pure char.



The quantity x is defined as the mass fraction of pure plastic in this imaginary mixture which yields the correct local density:

$$x = \frac{\rho_p}{\rho_p - \rho_c} \left(1 - \frac{\rho_c}{\rho} \right) \quad (5)$$

The thermal conductivity k will be weighted in the same manner unless the user provides specific information on a more complex x weighting in the input data. That is, the user may input functions of x for the following equation for the thermal conductivity of partially degraded plastic:

$$k = f_1(x)k_p + f_2(x)k_c \quad (6)$$

References 4 and 5 present an account of the rationale for the use of f -functions, along with recommended values.

The pyrolysis gas enthalpy is an input temperature dependent function (see Section 3.1.8 below). The quantity $\bar{h} \triangleq (\rho_p h_p - h_c \rho_c) / (\rho_p - \rho_c)$ is computed from temperature dependent h_p and h_c values determined from the input temperature dependent C_{pp} and C_{pc} values and input enthalpies of formation ΔH_{fp} and ΔH_{fc} .

Determination of the local cross-section area A will be discussed in Section 2.1.3 below.

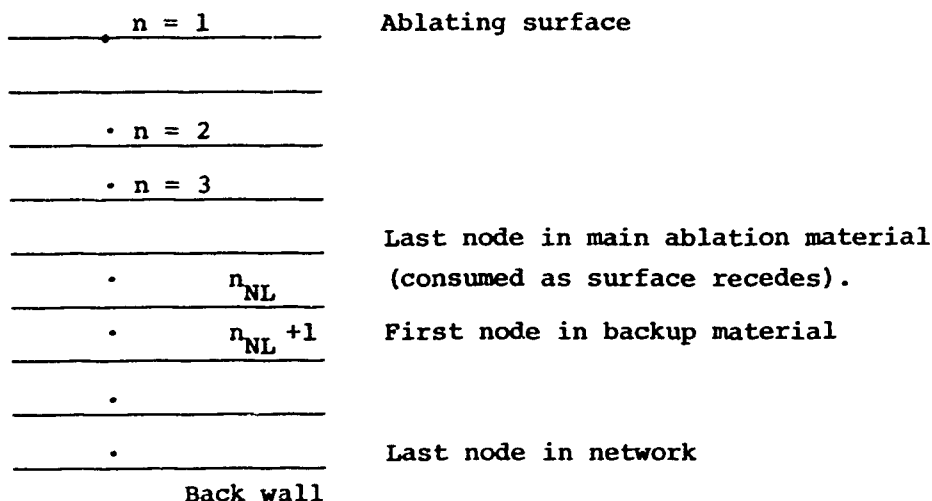
The other quantities in Equation (3), T , ρ and \dot{S} are dependent quantities discovered during the solution process (except that in some boundary condition options \dot{S} may be input).

2.1.3 Nodal Coordinate Layout and Body Shape Specification

The basic solution procedure of the CMA code is of the finite difference type. The following sketch illustrates a typical material section that is to be analyzed. Nodal* positions are specified by tabulating the thickness of successive nodes (see Section 3.1.5 below). The program permits a thermal contact resistance between adjacent nodes, and thus between adjacent materials (see Section 3.1.5 below). Nodes are numbered sequentially from the surface. A total of 100 nodes is permitted.

*As used here, the term node refers to a finite region in the slab wall, not to a discrete point or plane.

In harmony with the shifting x-coordinate system introduced in Section 2.1.2, nodal coordinates are tied to the heated surface. Any surface recession causes the last (deepest) node in the ablating material to shrink. If surface recession proceeds far enough, this node is dropped from the rear surface of the ablating material and the number of nodes reduced by one. Computation ceases when only one node of the main material remains.



Sketch of Nodal Network

The nodes are used for all energy balance calculations.

Since decomposition rates depend exponentially on temperature the decomposition calculations in the main material proceed on the basis of a "nodelet" network using small nodes a fraction as large* as the specified nodal layout used in energy balance calculations.**

The decomposition events are computed for each nodelet. The total density change for each node is taken as the sum of the nodelet density change rates.

The program permits the specification of a number of geometries:

1. Plane
2. Cylindrical or annular, with heated surface either inner or outer

* Usually one-tenth, although the number of nodelets per node may be selected by the user (see Section 3.1.3 below).

** The nodelet device is not used in charring back-up materials, which generally pyrolyze rather slowly.

3. Spherical or spherical shell, with heated surface either inner or outer
4. General "thermal stream tube" geometry, area varying as depth to any power
5. General "thermal stream tube" geometry, area varying arbitrarily with depth.

The distinction between these five options is indicated by the user according to the input rules given in Section 3.1.5 below.

2.1.4 Computation Procedure

2.1.4.1 General Pattern

As in all finite difference procedures, each step of the solution is made over an incremental time step Δt . Each computational step has three main events: internal decomposition, internal energy balance, and surface boundary energy balance. Computation of the three events gives "new" values of nodal densities, pyrolysis gas flow, nodal temperatures, and surface temperature and ablation rate. The program is then ready for the next step.

The pyrolysis event is computed for each nodelet in the main material from Equation (2), summed over the three components. Summation over all nodelets in a node gives the nodal $\partial \rho / \partial t$ and contribution to \dot{m}_g . Note that "old" known nodal temperatures (interpolated into the nodelet locations) are used in the pyrolysis calculation.

The internal energy balance equation then is computed "implicitly" for each node, using "new" temperatures in the heat conduction terms. The energy balance is linked explicitly to the decomposition events, however, since the pyrolysis gas fluxes used in the energy balance are derived from the explicit decomposition calculation. The energy balance is also linked explicitly to the surface boundary condition through the use of an "old" surface recession rate in all convection terms involving fluxes of solids. All other links to surface events are implicit.

The "implicit" formulation of the in-depth nodal energy equations yields a tri-diagonal set of equations which is solved for the unknown temperatures in two passes of direct elimination. The first pass eliminates one unknown from each equation and leaves the equation for the first node (at the heated surface) with only one unknown. In surface boundary condition Option 2, this temperature is specified and so is known. In Options 1 and 3, the first node equation is non-linear and so the first nodal temperature must be discovered by an iterative procedure. This will be discussed in Sections 2.4.2 and 2.4.3.

In any case, once this nodal temperature is determined, the second elimination pass determines the other unknown nodal temperatures and the entire in-depth calculation is ready for a new time step.

2.1.4.2 Limitations on Time Step Size

Experience shows that the implicit solution procedure of the CMA program is almost always stable regardless of time step size, and thus has an important advantage over explicit procedures for which stability considerations severely limit the allowable time step size.

However, in order to assure a smooth progression of the solution, limitations must be imposed upon the time increments. The user may specify as input (see Section 3.1.3 below) a maximum allowable time step not to be exceeded under any circumstances. Certain other limits are computed automatically and may reduce the solution time step Δt below this value:

- Time steps are sized to limit the change of surface temperature during one step to approximately 50°R
- At the initiation of a problem, or when discontinuities are noted in the surface boundary condition option, the time step is reduced to 0.01 seconds, with subsequent values limited to twice the preceding value of the time increment.
- Time steps are limited so that recession during a time step, $S\Delta t$, does not exceed the thickness of the smallest nodelet in the system.
- After all these limits have been applied, the time step is reduced so that the time remaining to the next printout time is divided into an integral number of time steps of the current size (so that no sudden reduction in time step is required in order to match a printout time).

2.2 INITIAL CONDITION

As initial conditions, the user may specify the temperature of each node and in addition may call out each node in a charring material as either virgin plastic or pure char. This allows studies of pre-charred materials and re-start problems. Section 3.1.5 below describes the necessary input rules.

2.3 BACKWALL BOUNDARY CONDITION

Heat transfer from the backwall of the system is treated with a simple temperature-potential convective transfer plus a radiative term, both

communicating with a "reservoir" at temperature T_{res} . The convective coefficient, backwall emissivity (or emittance), and T_{res} are all input constants (see Section 3.1.5 below).

2.4 ABLATING SURFACE BOUNDARY CONDITIONS

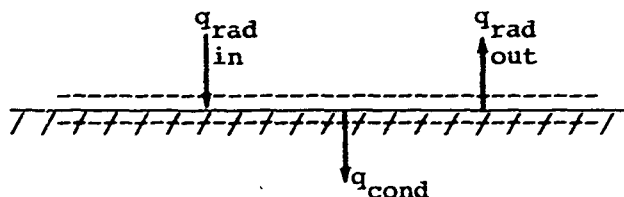
The ablating surface boundary conditions may take one of three forms at any instant, as determined by the user in the make-up of the time dependent boundary condition input table (see Section 3.1.9 below). The two simpler options will be described first, even though for historical reasons these are denoted "Option 2" and "Option 3". The general thermochemical ablation boundary condition, denoted "Option 1", is discussed last.

2.4.1 Option 2, Specified Surface Temperature and Surface Recession Rate

In this option, surface temperature and recession rate are specified by the user as input functions of time. All surface energy balance and surface thermochemical considerations are bypassed. Section 2.1.4.1 above describes how this specified temperature can be inserted into the in-depth solution procedure after the first pass of direct elimination.

2.4.2 Option 3, Specified Input Heat Flux with Zero Surface Recession Rate (Cooldown Option)

The following sketch illustrates the surface energy balance situation for this option. Equation (7) is the appropriate surface energy balance equation



$$\alpha_w q_{rad} - F_3 \sigma \epsilon_w T_w^4 - q_{cond} = 0 \quad (7)$$

In this equation, α_w is the surface absorptance and is assumed to equal ϵ_w , the surface emissivity, which is computed from input temperature dependent property tables (see Section 3.1.7 below). If the surface material is partially pyrolyzed, ϵ_w is computed according to the mixture rule of Equation (4). The term q_{rad} is an input time dependent heat flux specified in the boundary condition time tables (see Section 3.1.9 below). F_3 is an input view factor for

Option 3 calculations. It may depend on time (see Section 3.1.9 below). The term q_{cond} represents the rate of heat conduction into the material. It is the "mechanism" which joins the surface energy balance equation to the first nodal energy balance (since q_{cond} appears in the nodal energy balance equation) and thus to the in-depth solution procedure, as discussed in Section 2.1.4.1 above. The first pass of the elimination process for the in-depth tri-diagonal system reduction leaves the nodal energy balance equation for the first node as

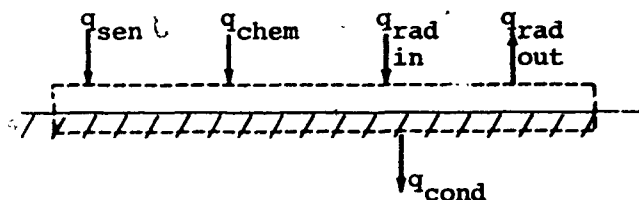
$$q_{\text{cond}} = AT_w + B \quad (8)$$

Equation (8), when substituted into the surface energy balance equation (7), yields a non-linear equation in T_w which the CMA program solves iteratively by the Newton-Raphson method.

2.4.3 Option 1, General Convective Heating and Thermochemical Erosion Option

2.4.3.1 General Description and Basic Energy Equation

In this option, events at the heated surface are determined by convective heating and by surface thermochemical interactions with the boundary layer gases. The sketch below illustrates the surface control volume and the



Sketch of Surface Energy Balance Control Volume and Energy Fluxes in Option 1

energy fluxes of interest. The surface energy balance equation employed is of the convective transfer coefficient type. In the CMA/CBM program, this energy balance equation takes the following form:

$$\underbrace{\rho_e u_e C_H (H_r - h_{ew})}_{q_{\text{sen}}} + \underbrace{\rho_e u_e C_M \left[\sum (z_{ie}^* - z_{iw}^*) h_i^{T_w} - B' h_w \right] + \dot{m}_c h_c + \dot{m}_g h_g}_{q_{\text{chem}}} + \underbrace{\alpha_w q_{\text{rad}}}_{q_{\text{rad in}}} - \underbrace{F \sigma \epsilon_w T_w^4}_{q_{\text{rad out}}} - q_{\text{cond}} = 0 \quad (9)$$

The last three terms in Equation (9) are the same as in the Option 3 boundary condition previously discussed in Section 2.4.2 above. The other terms in this equation require some further comments.

Before commencing a term by term discussion of Equation (9), however, it will be useful to describe the general nature of this transfer coefficient expression. Like all such expressions, Equation (9) is an approximation, the usefulness of which depends mainly on the validity of the transfer coefficient approach. A discussion of this subject is far beyond the scope of the present document. It may be observed here that transfer coefficients have successfully correlated both data and "exact" solutions in simple heat or mass transfer problems, and in combined heat and mass transfer problems for unity (or near unity) Lewis number. Equation (9) attempts to extend the transfer coefficient approach to both non-unity Lewis number and unequal mass diffusion coefficient problems, still allowing for chemical reactions and net mass transfer effects. This approach was suggested in Reference (6). Its validity is discussed in References 1 and 7.

In Equation (9), the term q_{sen} represents the "sensible convective heat flux." Physically, this is the convective heat flux which would occur for a frozen boundary layer and a non-catalytic wall in the absence of mass transfer;* it excludes all chemical energy contributions. (The term q_{sen} is perhaps more usually written in the form

$$q_{sen} = \rho_e u_e C_H (H_{s_r} - h_{s_w}) \quad (10)$$

but, since generally it is more convenient for the user to input H_r rather than H_s , q_{sen} in Equation (9) has been written in a modified form in which H_r appears. This form has the additional advantage that the driving force for energy transfer involves only edge gas states. The derivation of the modified form from Equation (1) is given in Reference 1 and Reference 6.

The transfer coefficient $\rho_e u_e C_H$ and the recovery enthalpy H_r are time dependent variables input by the program user in appropriate time tables (see Section 3.1.9 below). The transfer coefficient is automatically modified from the input value to account for various effects, as discussed in Section 2.4.3.4 below. The quantity h_{e_w} is part of the input thermochemical data discussed below.

* More generally in the presence of chemical reaction it is the diffusive heat flux from the gas to the wall even in the presence of net mass transfer, provided the boundary layer is frozen and the wall is catalytic.

The term q_{chem} represents the net of a number of fluxes of chemical energies at the surface. The Z^* -difference term represents transport of chemical energy associated with chemical reactions at the wall and in the boundary layer; it is the chemical energy parallel to the sensible convective heat flux term. The Z^* driving forces for diffusive mass transfer include the effects of unequal diffusion coefficients; for equal diffusion coefficients the Z^* 's reduce to the familiar mass fractions K . The $\dot{m}_c h_c$ and $\dot{m}_g h_g$ terms represent energy fluxes arriving at the surface from within the solid material and the $B' h_w$ term represents energy leaving the surface in the gross motion (blowing) of the gas adjacent to the surface.

The source of the various terms in q_{chem} can better be visualized after a slight regrouping of terms. Observing that $B' = B'_g + B'_c$, and bringing the $\dot{m}_c h_c$ term inside the brackets, we have

$$q_{\text{chem}} = \rho_e u_e C_M \sum (Z_{ie}^* - Z_{iw}^*) h_i^{T_w} - (B'_c + B'_g) h_w + B'_c h_c + \dot{m}_g h_g \quad (11)$$

Of the quantities in this q_{chem} expression, the convective mass transfer coefficient $\rho_e u_e C_M$ is obtained from the input time dependent values of $\rho_e u_e C_H$ (after any of the adjustments described in Section 2.4.3.4 below), by multiplying $\rho_e u_e C_H$ by an input constant value C_M/C_H (see Section 3.1.10.2 below). The quantity \dot{m}_g will have been determined previous to the energy balance calculations in each time step in the decomposition section of the code (see Section 2.1.4.1 above). The quantity B'_g may be found as its definition $B'_g = \dot{m}_g / \rho_e u_e C_M$. The enthalpy h_c is obtained from integrations of the input temperature dependent specific values C_{p_c} (see Section 3.1.7 below). The pyrolysis gas enthalpy is obtained from the input temperature dependent h_g table (see Section 3.1.8 below).

Remaining quantities not yet discussed are B'_c , T_w (which does not appear explicitly but which is necessary to evaluate the temperature dependent values of the quantities h_c and h_g), h_{ew} , $\sum Z_{ie}^* h_i^{T_w}$, $\sum Z_{iw}^* h_i^{T_w}$, and h_w . The quantities T_w , $\sum Z_{iw}^* h_i^{T_w}$, and h_w are input by the user as the dependent variables in a table with three independent variables: P , B'_g , and B'_c . Similarly, the quantities $\sum Z_{ie}^* h_i^{T_w}$ and h_c are input as the dependent variables in a table with P and T as independent variables. These tables are typically generated by the thermochemistry codes described in Section 2.4.3.2 below. Further discussion of these tables is given in Section 3.1.10.3.

The code surface energy balance solution procedure may be summarized as follows:

1. Look up H_r , $\rho_e u_e C_H$, P , and q_{rad} in input functions of time tables
2. Correct or adjust $\rho_e u_e C_H$ for various effects
3. Compute $\rho_e u_e C_M = C_M / C_H (\rho_e u_e C_H)$
4. Compute $B'_g = \dot{m}_g / \rho_e u_e C_M$
5. Assume B'_c
6. With P , B'_g , B'_c , look up in input surface thermochemistry tables values of T_w , $\sum z_{iw}^* h_i^{T_w}$, h_w
7. With ρ and T_w , look up in input edge gas thermochemistry table values of $\sum z_{ie}^* h_i^{T_w}$, h_{e_w}
8. With T_w , look up in input property tables values of ϵ_w , h_c , h_g
9. Obtain values of A and B in expression $q_{cond} = AT_w + B$ from in-depth nodal energy balance solution routine
10. Construct Equation (9), noting departure from zero, if any
11. Adjust B'_c guess to reduce departure from zero
12. Go to Step (6) and continue

This procedure converges on a new B'_c value in very few iterations. The same procedure is used with T_w as the independent variable and B'_c as a dependent variable in portions of the table where B'_c varies slowly or not at all with T_w (see Section 3.1.10.3 below for input rules and suggestions).

2.4.3.2 Use of Thermochemistry Codes to Generate Input Data

Section 2.4.3.1 above makes it clear that the CMA code requires some complex tabular thermochemical input if the Option 1 boundary condition is to be used. These tables are generated by any one of a number of separate computer codes. The most recent such code is designated the Equilibrium Surface Thermochemistry Code, Version 3 (EST3). It is a general open and closed system thermochemical equilibrium code specifically constructed for this purpose. It is described in Reference 8. A generally similar code which differs from EST3 only in added detail is designated ACE and is described in Reference 9. An older version of EST3 was designated EST2 and is described in Reference 10. To obtain the necessary input tables for CMA, the user selects sets of values for the pressure P , the dimensionless gas rate B'_g , and the dimensionless char

rate B'_C . He specifies the elemental composition of the environment gas, the char, and the pyrolysis gas, and he supplies some general species thermochemical data for all molecules he wishes considered in the system. Finally he specifies an unequal diffusion coefficient if he believes unequal diffusion effects will be important. The thermochemistry code then computes all the dependent quantities of interest at each table point in the $P \times B'_g \times B'_C$ matrix of independent variable values, namely, T_w , $\sum_{iw}^* h_i^{T_w}$, and h_w , and punches this information out on punched cards. Similarly, the tables of $\sum_{ie}^* h_i^{T_w}$ and h_e values for the frozen edge gas are prepared as functions of P and T , and punched out on cards. All these cards form part of the card input deck (see Section 3.1.10.3 below).

2.4.3.3 Simpler Forms of the Surface Energy Balance Equation

As noted in Section 2.4.3.1 above, for equal diffusion coefficients the Z_i^* driving forces reduce to the simple mass fractions K_i . If in addition to equal diffusion the user specifies that $\rho_e u_e C_H = \rho_e u_e C_H$, then since $\sum_{ie} K_i h_i^{T_w} = h_{ew}$ and $\sum_{iw} K_i h_i^{T_w} = h_w$ by definition, Equation (9) simplifies to the more familiar form

$$\rho_e u_e C_H (H_r - (1 + B') h_w) + \dot{m}_c h_c + \dot{m}_g h_g + \alpha_w q_{rad} - F_1 \sigma \epsilon T_w^4 - q_{cond} = 0 \quad (12)$$

In this expression h_{ew} and $\sum_{ie}^* h_i^{T_w}$ do not appear, hence the frozen edge gas table is not necessary and need not be included in the input (see Section 3.1.10.3 below).

If ablation and pyrolysis do not occur, Equation (12) assumes a still simpler form

$$\rho_e u_e C_H (H_r - h_w) + \alpha_w q_{rad} - F_1 \sigma \epsilon T_w^4 - q_{cond} = 0 \quad (13)$$

Section 3.1.10.3 below will make it clear that this equation can be handled by the CMA code through the mechanism of "non-ablating" surface thermochemistry tables. Equation (13) can be reduced to a temperature driving force, if this is desired

$$h(T_r - T_w) + \alpha_w q_{rad} - F_1 \sigma \epsilon T_w^4 - q_{cond} = 0 \quad (14)$$

provided that the user enters T_r instead of H_r and h instead of $\rho_e u_e C_H$ in the boundary condition time tables (see Section 3.1.9 below), and T_w instead of h_w in the surface thermochemistry tables (see Section 3.1.10.3 below).

2 4.3.4 Automatic Program Adjustments to Input Values of Time-Dependent Convective Heat Transfer Coefficient $\rho_e u_e C_H$

2.4.3.4.1 General remarks

The CMA program user may call for several automatic adjustments to be made to the values of the convective transfer coefficient input in the functions-of-time table. This section describes these adjustments and the order in which they are applied in the program.

One adjustment, pertinent to the exposed throat ablative materials in rockets, is the "radius ratio correction." This adjustment accounts for the effect of pressure decay and throat radius change on the throat transfer coefficient, provided, as will be explained below, that the trends of the effects are given by the Bartz equation (Reference 11). A refinement to this basic correction includes the additional effect of pressure on the burning rate of a solid propellant. A second refinement on the throat radius ratio correction allows in an approximate manner for the effects of char swelling.

A second correction allows for the reduction in transfer coefficients due to the transpiration or blowing effect of the pyrolysis gases and thermochemically eroded char being injected into the boundary layer.

A final modification distinguishes the convective mass transfer coefficient $\rho_e u_e C_M$ from the heat transfer coefficient $\rho_e u_e C_H$ by referring to an input constant ratio C_M/C_H .

2.4.3.4.2 Radius ratio correction, burning rate correction, and char swell correction

Radius ratio and burning rate corrections

If the user is analyzing a solid propellant rocket throat ablation problem, and calls for the throat radius ratio correction according to the input procedures described in Section 3.1.10.3 below, the program, will, at every time step, automatically reduce the input time table value of C_H to account for the effects of the increase in throat radius resulting from ablation. The correction is derived by noting that for a solid rocket motor

$$p_c \propto \left(\frac{1}{r^*} \right)^{2/(1-n)} \quad (15)$$

where p_c - chamber pressure
 r^* - nozzle throat radius
 n - burning rate exponent of the solid propellant when the burning rate \dot{r} , is represented by $\dot{r} = b p_c^n$

From the simplified Bartz equation

$$h_c \propto \frac{p_c^{0.8}}{r^{*0.2}} \quad (16)$$

where h_c is the convective heat transfer coefficient. Combining these two equations gives

$$h_c \propto \left(\frac{1}{r^*} \right)^{\frac{1.8-0.2n}{1-n}} \quad (17)$$

For $n = 0$, this equation reduces to

$$h_c \propto \left(\frac{1}{r^*} \right)^{1.8} \quad (18)$$

and would represent the correction in the convective heat transfer coefficient for a constant mass flow rate. This is usually termed the radius ratio correction.

The CMA program refers the time table values of C_H to the initial condition. This, if C_{H_0} represents the input heat transfer coefficient at a given time, the program will reduce the input value according to

$$C_{H_1} = C_{H_0} \left(\frac{r_1^*}{r^*} \right)^{\frac{1.8-0.2n}{1-n}} \quad (19)$$

if the radius ratio correction has been called for.

Char swell correction

It has been determined empirically that certain phenolic materials swell or thicken during or following charring. The amount of swell has in some cases (References 12 and 13) appeared to be roughly proportional to the thickness of the charred material:

$$S_{\text{swell}} = K \tau_{\text{char}} \quad (20)$$

where K is a proportionality constant.

The char thickness (τ_c) is here defined as the char depth below the original surface (δ_c)* minus the surface recession predicted in the absence of swelling (S_p)

$$S_{\text{swell}} = K(\delta_c - S_p) \quad (21)$$

Therefore, if swell occurs, the correct recession would be given by:

$$S = S_p - S_{\text{swell}} = S_p - K(\delta_c - S_p) \quad (22)$$

or

$$S = S_p + (S_p - \delta_c)K \quad (23)$$

Furthermore, surface recession rate would be given by:

$$\dot{S} = (1 + K)\dot{S}_p - K\dot{\delta}_c \quad (24)$$

For a given value of K , these terms are computed in the CMA code and output in an auxiliary output block. In addition, if adjustments in heat transfer coefficient by a radius ratio correction are being computed as is often the case with prediction of rocket nozzle throat response, the corrected (after swell) value of recession is utilized in the radius ratio correction calculation. Otherwise this char swell formulation is not used in the thermal response calculations.

2.4.3.4.3 Blowing rate correction

The CMA program will automatically reduce the transfer coefficient to account for the familiar blowing effect according to the equation

$$C_H = C_{H1} \frac{\zeta}{e^\zeta - 1} \quad (25)$$

where

$$\zeta \triangleq \frac{2\lambda \dot{m}_{\text{inj}}}{\rho_e u_e C_{H1}}$$

*The distance δ_c is defined as the distance between the original location of the heated surface and the present location of a line of density $\rho_c + r_c(\rho_p - \rho_c)$, where r_c is a user-selected input constant (see Section 3.1.6 below).

and \dot{m}_{inj} = amount of material injected into the boundary layer, as discussed below

λ = an input number, discussed below

$\rho_e u_e C_{H_1}$ = transfer coefficient as input and reduced, if required, by the radius ratio and/or burning rate effect discussed in the section immediately above.

Further details of this correction scheme will be discussed below.

Values for λ

With $\lambda = 0.5$, this scheme gives the "classical" blowing correction often expressed as (References 14 and 15)

$$\frac{C_H}{C_{H_1}} = \frac{\ln(1 + \dot{m}_{inj}/\rho_e u_e C_H)}{\dot{m}_{inj}/\rho_e u_e C_H} \quad (27)$$

which is useful for a wide range of problems.

Other values of λ allow the user to fit blowing correction curves of C_H/C_{H_1} versus B'_{inj} or B'_{inj1} to account for special effects, in the few cases where these are known with confidence, such as molecular weight effects* or variable property effects. In view of the uncertainties, it is recommended that $\lambda = 0.5$ be used for laminar flow. A value $\lambda = 0.4$ appears to correlate constant properties turbulent data somewhat better. The parameter λ may be made a function of time, if desired, to simulate transition effects. A value of $\lambda = 0$ suppresses the blowing correction.

Options for \dot{m}_{inj}

The symbol \dot{m}_{inj} represents the rate of mass injected into the boundary layer which is effective in changing velocity profiles and reducing diffusion events. The CMA program allows three general choices for \dot{m}_{inj} :

1. All mass transfer is effective in reducing blowing

$$\dot{m}_{inj} = \dot{m}_c + \dot{m}_g$$

2. If part of \dot{m}_c represents failing species, and this failing component \dot{m}_{fail} appears on the surface thermochemistry cards (an ACE output option), then these fail rates can, at the option of the user (see Section 3.1.10.3 below) be read in,

*These are known to be important in some simple injection problems but with many chemical reactions taking place the situation is somewhat obscure.

stored, and deducted as appropriate when computing injection rates for the blowing correction

$$\dot{m}_{inj} = \dot{m}_c - \dot{m}_f + \dot{m}_g$$

3. It can be assumed that the pyrolysis gas is injected into the boundary layer through cracks and fissures rather than evenly over the heated surface; in this case the gas injection presumably plays no role in the blowing reduction, in which case

$$\dot{m}_{inj} = \dot{m}_c$$

or

$$\dot{m}_{inj} = \dot{m}_c - \dot{m}_f$$

if Option 2 above is being used. This fissure model is discussed in more detail in Section 2.4.3.5 below.

The CMA program automatically computes the injection rate \dot{m}_{inj} according to the first option above unless the fail option has been invoked according to the input rules discussed in Section 3.1.10.3 below and unless the fissure model has been called for as described in the same section.

Blowing correction applied to C_{H_1}

Note that the blowing correction is applied to the value of C_H after it has been adjusted to account for the radius ratio (including burning rate and char swell) effect.

2.4.3.4.4 Computation of convective mass transfer coefficient $\rho_e u_e C_M$

After $\rho_e u_e C_H$ has been computed from the input time dependent value $\rho_e u_e C_{H_0}$ and corrected, if called for, for radius ratio and mass transfer effects, a mass transfer coefficient $\rho_e u_e C_M$ is computed by multiplying $\rho_e u_e C_M$ by an input constant ratio C_M/C_H . See Section 3.1.10.3 below.

2.4.3.4.5 Possible future additional corrections

The automatic adjustments to input values of $\rho_e u_e C_{H_0}$ presently included in the CMA program include the largest and most important corrections the user is likely to desire. A small temperature correction might occasionally be of interest but has not yet been added to the program. A molecular weight effect in the blowing correction must for the present be accounted for by adjusting λ ; this probably will yield adequate accuracy until more is known about

(1) the desired molecular weight effect, and (2) the molecular weight of the pyrolysis gas component of the injected material.

2.4.3.5 Fissure Model Option for Surface Energy Balance

Equation (9), which is repeated here for reference, includes the energy efforts associated with injecting the pyrolysis

$$\rho_e u_e C_H (H_R - h_{e_w}) + \rho_e u_e C_M \sum (Z_{ie}^* - Z_{iw}^*) h_i^{T_w} - B' h_w + \dot{m}_c h_c + \dot{m}_g h_g + \alpha_w q_{rad} - F \sigma \epsilon_w T_w^4 - q_{cond} = 0 \quad (28)$$

gas rate \dot{m}_g into the surface from below with enthalpy h_g and "blowing" a corresponding flux away from the surface with enthalpy h_w (included in the $B' h_w$ term). However, some ablative materials crack or fissure during heating and sometimes it is desired to explore the effects of assuming that the pyrolysis gas follows these fissures to the surface and is blown out through the boundary layer without participating to any great degree with the boundary layer events. Specifically, in the "fissure model", the $\dot{m}_g h_g$ injection energy term in the surface energy balance is matched by an equal $\dot{m}_g h_g$ outflow term as the gas passes across the surface without interacting. By the same token, the blowing term $B' h_w$ now becomes $(B' - B'_g) h_w$, since the B'_g blowing effect has been isolated and identified with enthalpy h_g rather than h_w .

Thus, the "fissure model" surface energy balance equation is

$$\rho_e u_e C_H (H_R - h_{e_w}) + \rho_e u_e C_M \sum (Z_{ie}^* - Z_{iw}^*) h_i^{T_w} - B'_c h_w + \dot{m}_c h_c + \alpha_w q_{rad} - F \sigma \epsilon_w T_w^4 - q_{cond} = 0 \quad (29)$$

Suitable programming has been implemented in the current CMA code to allow utilization of this model with only minimal adjustment of input data.

The user may call for this surface energy balance type by punching the fissure model flag in the lead card for the surface thermochemistry tables (see Section 3.1.10.3 below).*

When using this model, the user generally makes two other modifications to the usual input. First to harmonize the in-depth calculations with the idea of the pyrolysis gas rising up cracks and fissures, pyrolysis gas thermal pick-up in the char is suppressed by artificially "flattening" the gas enthalpy-temperature relationship (see Section 3.1.8 below) for temperatures above the pyrolysis temperature (i.e., $C_{pg} = 0$ in this temperature range). Second, the surface thermochemistry tables are prepared for $u_g = 0$ so as to exclude any surface thermochemical effects of the pyrolysis gases. Since the interpolation routine requires two B'_g values for a given pressure, the $B'_g = 0$ table is duplicated and the duplicate is assigned a second, artificial B'_g value.

2.4.3.6 Accounting For Condensed Phase Removal (Melting or "Failing")

The surface energy balance Equation (9) does not show an energy term corresponding to condensed phase removal (as in thin layer melting or failing) but failing is detected by the ACE surface state program and the associated energy effect is automatically accounted for in the surface thermochemistry tables. The ACE User's Manual, Reference 13, describes the melting or failing features of that code and provides detailed instructions for implementing them. The EST3 code cannot account for failing.

*This flag also causes B'_g not to be included in the blowing reduction calculation for the transfer coefficients (see Section 2.4.3.4 above).

SECTION 3

USER'S GUIDE

This part of this report provides

- Detailed user oriented input instructions for the CMA code
- An explanation of the program output
- Miscellaneous specific information

3.1 INPUT FORMAT

The input to the Charring-Material Thermal Response and Ablation Program, Version 3, can conveniently be divided into ten parts. All ten portions of the deck must be present for most runs. These individual parts will be described in the following subsections.

3.1.1 Title and Heading Information

The first three cards of the data deck are used to transmit title and heading information to the output. The first 72 columns of each of these cards may be used for the title, the alphanumeric information in columns 61 through 72 of the third card being used as a page heading on all pages after the first.

3.1.2 Internal-Decomposition Kinetic Data

These three cards supply the constants used in Equation (2).^{*} They are supplied according to the following format.

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
1	I1	Alphabetic character A, B, or C referring to the material components. These must be on the first, second and third cards of this set in order	
11-20	F10.5	Initial density of component i, ρ_{0i}	lb/ft ³
21-30	F10.5	Residual density of component i, ρ_{ri}	lb/ft ²
31-40	F10.3	Pre-exponential factor, B_i , of Equation (2)	sec ⁻¹
41-50	F10.5	Density factor exponent, ψ_i	---

^{*}Reference 4 cites relevant data for many materials of interest.

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
51-60	E10.3	Activation energy factor ($E_{a_i}/^{\circ}\text{R}$)	$^{\circ}\text{R}$
61-70	F10.5	Minimum temperature of reaction zone	$^{\circ}\text{R}$
71-79	---	Not read	---
80	---	(Third card only) Number (0 to 5) of decomposing (pyrolyzing) back-up materials in this problem	---

In this table, the minimum temperature of the reaction zone is included only as a means of reducing computational time. Thus, if a nodal temperature is below this value, the program will bypass the fairly complex density-calculation procedure. Also for the case of a non-decomposing reinforcing material, the value of this temperature can be set to a ridiculously high value, thus assuring no decomposition.

3.1.3 Output Interval Specification and General Program Constants

Two cards are used to provide the program with the values of certain general constants, to establish the time intervals for which output will be obtained, and to specify thermocouple and isotherm output, if desired. (If thermocouples and/or isotherms are called for, additional cards are needed, as described.)

First Card

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
1-2	I2	Number of nodelets per node (blank implies 10)	---
3-5	I3	Total number of nodes (maximum of 100)	---
6	I1	A non-zero punch in this column will cause thermocouple and isotherm output, normally listed with regular output, to <u>also</u> be punched as cards	---
7-8	I2	Number of thermocouples for which output is desired. (The depths of these thermocouples are specified on additional cards of this group.) Punches here will cause thermocouple temperatures as a function of time to be output at the end of the regular program output.	---
9-10	I2	Number of isotherms for which output is desired. (The temperatures of these isotherms are specified on additional cards of this group.) Punches here will cause isotherm depths as a function of time to be output at the end of the regular program listing.	---

First Card (concluded)

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
11-20	F10.5	Initial value of time	sec
21-30	F10.5	Final value of time	sec
31-40	F10.5	Initial output time interval	sec
41-50	F10.5	Second output time interval	sec
51-60	F10.5	Third output time interval	sec
61-70	F10.5	Maximum time step permitted under any circumstances. If unpunched, this limit will be set equal to 5.0 seconds	sec
71-80	F10.5	Blowing-rate parameter, λ	---

Second Card

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
1-10	F10.5	Time of transition from initial to second output time interval	sec
11-20	F10.5	Time of transition from second to third output time interval	sec
21-30	F10.5	Minimum thickness of last ablator node. When because of surface recession, the last node of the ablation material shrinks below this value, it is combined with the adjacent ablator node. A value equal to the second node's thickness is usually appropriate	in
31-40	F10.5	Heat of formation of the virgin plastic, the char, and the pyrolysis gas, respectively. These are evaluated at the datum temperature given in columns 71-80	Btu/lb
41-50	F10.5		
51-60	F10.5		
61-70	F10.5	Volume fraction or mass fraction of the virgin plastic which is occupied by resin. If mass fraction, it is input as a negative number	---
71-80	F10.5	Datum temperature for heats of formation given in columns 31-50. For Option 1 computations, this must be the same temperature as used in the EST program for generating the surface thermochemistry data deck.	$^{\circ}\text{R}$

Additional Cards as Required

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
1-80	8(F10.5)	If thermocouple and/or isotherm output have been called for, these cards specify thermocouple depths in inches below the original surface and isotherm temperatures in degrees Rankine. Isotherm temperatures must begin on a new card. The total number of thermocouples and isotherms may not exceed 20. If no thermocouples or isotherms are called for, these card(s) are omitted.	in and/or °R

3.1.4 Back-Up Material Decomposition Data (Optional)

If the problem includes decomposing (pyrolyzing) back-up materials, a four card set of pyrolysis data must be included for each such decomposing back-up material. Each four card set has two subgroups:

o First Subgroup:

Back-Up Material Decomposition Kinetic Data (3 Cards)

Three cards in the format of the three kinetic data cards for the main material, except that column 80 of Card 3 is not read. Groups 4a (three cards) and 4b (one card) are placed together as a four-card unit. There will be one such four-card unit for each decomposing back-up material.

o Second Subgroup:

Enthalpies of Formation, Resin Volume, Or mass Fraction, Enthalpy Reference Temperature (1 Card)

This card follows the same format as the second card of Section 3.1.3 except that general data on that card not pertinent to the back-up material is not needed and is not read:

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
1-30	<u>ad lib</u>	Not read	---
31-40	F10.5	Heats of formation of virgin plastic and char,	Btu/lb
41-50	F10.5	respectively, evaluated at the datum temperature given in columns 71-80	
51-60	<u>ad lib</u>	Not read	---
61-70	F10.5	Volume fraction or mass fraction of the virgin plastic back-up which is occupied by resin. If mass fraction, it is input as a negative number	---
71-80	F10.5	Datum temperature for heats of formation.	°R

3.1.5 Nodal Data

A set of cards equal in number to the number of nodes is used to provide certain information with regard to the initial state of the nodes, their thickness, and the contact resistances between them. In addition, the first card of this set is used to specify the geometric nature of the exposed surface, that is whether it is a flat plate or an internal or external radius. The format for these cards is shown in the following table.

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
1-2	I2	Material number, 1 for main material virgin plastic, 2 for main material char, 0 for main material pyrolysis zone (can not be input), 22-31 for charring back-up materials (see discussion below), and 3-10 for non-charring back-up materials	---
3-12	E10.0	Initial temperature of the node	$^{\circ}\text{R}$
13-22	E10.0	Initial cross-sectional area of the node in any units or normalized on any convenient reference such as the surface area. This data is required only for "general" geometries; for planar, cylindrical, and spherical geometries, and for shapes for which the area varies as a power of the radius the specification of individual nodal areas is not required and these columns should be left blank	Arbitrary
23-32	E10.0	Initial thickness of the node (For suggestions on the selection of nodal thicknesses, see Appendix A.)	in
33-42	E10.0	<p><u>First card only.</u> 0 for planar surface; positive value of internal radius or negative of value of external radius for all non-planar axisymmetric geometries (including spheres and shapes with $A \sim r^a$)</p> <p><u>Second card only.</u> Exponent on radius giving nodal cross-sectional area variation for spherical and other "regular" geometries. Sphere requires 2.0. No entry needed for planar and cylindrical geometries. Must be blank if "general" geometry option is used</p>	in
43-52	E10.0	Contact resistance between this node and the next node.	$\text{ft}^2\text{sec-}^{\circ}\text{R/Btu}$
53-80	38X	NOT USED	

The number of nodes may not exceed 100. Note that for a restart calculation, the nodes that make up the precharred depth in the main material are called out as material 2.

In the list of nodes, any decomposing back-up material nodes will appear between the last node of the main ablating material and the first node of non-charring back-up (if any). Material numbers of the charring back-ups must be assigned as follows:

	<u>Virgin</u>	<u>Char</u>
1st charring back-up	22	23
2nd charring back-up	24	25
3rd charring back-up	26	27
4th charring back-up	28	29
5th charring back-up	30	31

The rules here differ from those for non-charring back-ups in that one charring back-up must be distinguished from another if it has a different location. For example, the fourth back-up may happen to be identical to the first, but it still receives a different material number.

3.1.6 Back Wall Heat Transfer Conditions; Char and Pyrolysis Zone Criteria

Heat transfer at the back wall is characterized by a convective heat transfer coefficient, an emissivity, and the temperature of a "reservoir" to which heat transfer takes place from the back wall. This card allows the specification of these three quantities. Blanks serve to specify an insulated back wall.

Two additional entries define char edge density and pyrolysis zone edge density according to the following definitions:

$$\rho_{\text{char edge}} = \rho_c + r_c (\rho_p - \rho_c)$$

$$\rho_{\text{pyrolysis edge}} = \rho_c + r_p (\rho_p - \rho_c)$$

The user inputs values for r_c and r_p . Typical values are $r_c = 0.02$ (defining the char edge as occurring where the density is $\rho_c + 0.02(\rho_p - \rho_c)$) and $r_p = 0.98$. If no entries are made for r_c and r_p , 0.02 and 0.98 will be assumed.

For char swell corrections, a value of $r_c = 0.5$ is suggested (see Section 2.4.3.4 above).

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
1-10	F10.5	Back wall convective coefficient	Btu/sec-ft ² °R
11-20	F10.5	Back wall emissivity	---
21-30	F10.5	Reservoir temperature	°R
31-40	F10.5	Char zone criterion r_c	---
41-50	F10.5	Pyrolysis zone criterion r_p	---
60	I1	One punch calls for output of thermal conductivity in place of enthalpy in standard output block	

3.1.7 Material Property Tables and f-Function Tables

In these tables are presented the requisite thermodynamic data for the main material virgin plastic (material no. 1), the main material char (material no. 2), any charring back-up materials, and the various non-charring back-up materials (materials 3 through 10, as required) specified in the nodal data table. These data are input as functions of temperature according to the following format.

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
1-2	I2	Flag, nominally zero, +1 marks terminal card of last material property table, -1 marks terminal card of other intermediate material property tables.	---
3-12	F10.5	Temperature (independent variable)	°R
13-22	F10.5	Specific heat	Btu/lb-°R
23-32	F10.8	Thermal conductivity	Btu/ft-sec-°R
33-42	F10.5	Emissivity	---

Separate tables must appear for the main material virgin plastic and the main material char, in that order. If the main material does not char, a "char" table must still be included. If charring back-up materials have been included in the problem, then paired tables must be given for the virgin plastic and char properties of all such back-ups, with the table pairs appearing in the same order with which such back-ups appear in the nodal list (see Section 3.1.5 above). If a charring back-up is duplicated, duplicate tables must be included

in the proper order. Tables for decomposing back-ups follow the two tables for the main charring material and precede any tables for non-charring back-ups.

Any necessary property tables for non-charring back-up materials follow these charring material tables. Preceding each such table, a single lead card" is used to specify the back-up material identification number and density. These data are given in the first ten columns with the following format.

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
1-2	I2	Material identification number (ranging from 3-10, inclusive)	---
3-10	F8.4	Material density	lb/ft ³

If the emissivity for materials 1 and 2 is input as zero, it is automatically presumed to be 1.0 for any Option 3 computations. (The user may desire to input a zero emissivity for radiation equilibrium problems under Option 1.)

The number of temperature points in each table may not exceed 30 or may not be less than 2. The tables must be ordered on either ascending or descending temperatures.

For all charring materials, material properties for partially degraded or charred material are formed from weighted averages of the plastic and char properties for the relevant nodal temperatures according to the mixture rules presented in Section 2.1.2 above. If the user wishes to employ the so called "f-functions" for this purpose (see Equation (11) of Section 2.1.2 above, the $f_1(x)$ and $f_2(x)$ values are input along with the other material properties tables described in this section. Each f-function table follows the following special rules:

- An f-function table is flagged by a lead card of the following format

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
1-2	I2	Identification flag which must be between 3 and 10 and which must not duplicate the identification number of a previously read non-charring back-up property table	---
3-10	F8.4	<u>Must</u> be blank or zero	---

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
11-16	6I1	Material assignment numbers for the following f-function table. If this table is assigned to the surface material, column 11 must be blank. If the same f-function table is to be assigned to one or more charring back-up materials, these assignments follow in columns 12-16 in any order with imbedded or following blanks being ignored. Note that for the material assignments in columns 11-16 of the lead card, the surface material is designated as zero (or blank) and the charring back-up materials are designated 1 through 5 in the same order as they appear in the nodal data cards. If column 11 is not blank, the f-function table will not be used for the surface material.	---

- The actual f-function table follows the lead card and has the following format

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
1-2	I2	Flag, as above, for last card of table	---
3-12	F10.5	x (independent variable)	---
13-22	F10.5	$f_1(x)$	---
23-32	F10.5	$f_2(x)$	---

- The f-function tables may be distributed anywhere among the non-charring back-up properties tables.
- If any charring material, main or back-up, is not assigned an f-function table, the thermal conductivity of partially charred substance for this charring material will follow the simple linear form of Equation (14).

3.1.8 Pyrolysis Gas Enthalpy Table

This table specifies the variation of pyrolysis gas enthalpy with temperature. These values are added to the heat of formation of the pyrolysis gas as specified on the program constant cards (see Section 3.1.3 above). This table is presented on card pairs, the first of which presents a set of temperature (up to 8), the second containing the corresponding enthalpy values. The first column of the temperature card is used as a flag, nominally blank but containing an integer to mark the last pair of cards. The format for this card pair is given as (I1, F9.5, 7F10.5/8F10.5), implying a basic field length of

ten columns for both temperature and enthalpy, with the exception of the first temperature which is restricted to columns 2 through 10. The temperatures should be given in ascending sequence with the exception of the last card pair which may have from one to eight entries). The total number of temperature points in the table may not exceed 30 and may not be less than 2.

Note that no pressure dependence of pyrolysis gas enthalpy may be accounted for. Also note that only one pyrolysis gas is allowed, and hence the gas given off by any charring back-ups must be the same as the pyrolysis gas of the main material, as would be the case, for example, for carbon phenolic backed by silica phenolic.

3.1.9 Surface Time-Dependent Boundary Conditions

The table of time-dependent boundary conditions is used to specify alternative sets of time-varying dependent variables for the various options. The table must be ordered with the time values increasing.

The table may be thought of as consisting of a number of sub-tables each sub-table representing one option. The switch from one option to another requires a repeated time entry, the first card representing the last entry of the earlier table and the second card representing the start of the next table.

The total number of time values in the table is limited to 30. Each sub-table must have at least 2 entries, hence the number of sub-tables cannot exceed 16. (The most common problem has only 2, representing an Option 1 or Option 2 calculation followed by cooldown, Option 3.)

The format for the time-tables is as follows:

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
1	I1	Flag, nominally blank, punched to indicate the last card of the time table. In any Option 1 calculations are to be done, this flag must be a one (which calls for reading the surface equilibrium tables). If no Option 1 calculations are to be done, this flag must be a two.	---
2-10	F9.5	Time (independent variable)	sec
11-20	F10.5	Option 1: Recovery enthalpy, relative to the same chemical base state as used with the heats of formation.	Btu/lb
		Option 2: Surface temperature	°R
		Option 3: Radiation view factor	---

<u>Columns</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
21-30	F10.5	Option 1: Radiant energy flux to the surface	Btu/ft ² -sec
		Option 2: Surface-recession rate	mils/sec
		Option 3: Radiant energy flux to the surface	Btu/ft ² -sec
31-40	F10.5	Option 1: Heat-transfer coefficient	lb/ft ² -sec
		Option 2: Blank	
		Option 3: <u>Must</u> be blank	
41-50	F10.5	Option 1: Pressure	atm
51-60	F10.5	Option 1: Blowing reduction parameter (if a function of time; blank entries will be filled by constant value entered in column 71-80 of the first card of Section 3.1.3 above).	

3.1.10 Surface Thermochemistry Data (Option 1 Only)

3.1.10.1 Introduction

As discussed in Section 2.4.3 above, problems involving use of the surface thermochemistry option (Option 1) require the input of an array of surface mass and energy data particular to the option and the material being analyzed. These data include the specification of the ratio of mass transfer coefficient to heat transfer coefficient, the radiation view factor, and surface thermochemical data. The cards containing this input are described below. Problems not involving Option 1 calculations do not need the surface thermochemistry data deck.

3.1.10.2 Ratio of Mass to Heat Transfer Coefficient, View Factor, Surface Option Flags

A single card serves to specify the ratio of the convective mass transfer coefficient to the convective heat transfer coefficient (C_M/C_H), the surface radiation view factor, and a number of control flags. (The view factor on this card will only be used for Option 1 computations. For Option 3 (cool-down) computations, a separate Option 3 view factor is input as a function of time in the functions-of-time tables. In Option 1 problems with "radiation equilibrium", the radiant energy flux to the surface may be input as zero, requiring then that the Option 1 view factor be input as zero.)

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
1-10	F10.0	C_M/C_H	---
11-20	F10.0	Option 1 view factor	---
21-29	F9.0	Burning rate exponent n used in throat problems to adjust input convective transfer coefficient $\rho_e u_e C_{H_0}$ according to	---

$$\frac{C_{H_1}}{C_{H_0}} = \left(\frac{r_{s0}}{r_s} \right)^{\frac{L_s \cdot A_2 n}{1-n}} \quad (30)$$

C_{H_1} is then adjusted to account for blowing effects. Applies to inner radius heating problems (nozzles) only. See Section 2.4.3.4 above.

30	11	One punch calls for radius ratio correction on input convection transfer coefficient $\rho_e u_e C_{H_0}$ according to Equation (30) above. Note: Input of n > 0 calls for Equation (30) and will override blank in this column. Applies to inner radius heating problems (nozzles) only.	---
31-39	9X	Blank	---
40	11	One-punch calls for reuse of previously input surface tables. No more input is read. Note: Ratio of C_M/C_H (columns 1-10) must be the same for this calculation as for previous one if this option is to be used.	---
50	11	One-punch reads B'_f in "new format" surface thermochemistry tables (as discussed below) and uses $B' - B'_f$ in blowing correction to $\rho_e u_e C_{H_0}$ or $B' - B'_g - B'_f$ if fissure model is being used, see column 60 below), no punch reads "old format" surface tables or ignores B'_f in "new format" tables and uses B' in blowing correction to $\rho_e u_e C_H$ (or $B' - B'_g$ in fissure model).	---
51-59	9X	Blank	---
60	11	One-punch invokes "fissure model": excludes B'_g from blowing correction on $\rho_e u_e C_{H_0}$ and from surface energy balance; see Section 2.4.3.5 above.	---
61-70	F10.0	Char swell proportionality constant K in Equation (21), section 2.4.3.4.2	---

3.1.10.3 Surface Thermochemistry Table

3.1.10.3.1 Introduction

This table supplies the necessary input data for the surface energy balance computations in Option 1. (This energy balance is discussed in Section 2.4.3 above.)

Most commonly the deck of cards which make up the surface thermochemistry table is generated by the Equilibrium Surface Thermochemistry (EST) program or the Aerotherm Chemical Equilibrium (ACE) program. The user's manual for these programs (References 8 and 9) describe this table in complete detail. On occasion, the user may desire to construct his own surface thermochemistry table, and so the following sections include brief descriptions of the organization and format of these tables. The main emphasis, however, will be on the communication between thermochemistry programs and the Charring Material Ablation program, since this is of the most general interest.

3.1.10.3.2 Edge enthalpy data

Equation (9) of Section 2.4.3 shows that if diffusion coefficients are not equal or if the ratio C_M/C_H is not unity, then the surface energy balance requires data about the edge gases of the boundary layer. These data are provided in a special "edge table". The independent variables for this table are pressure and temperature. Dependent variables are h_{ew} and the sum $\sum_{ie} Z_i^* h_i^T$.

The edge enthalpy data are entered on the cards as follows:

Column	Format	Data	Units
1-8	F8.5	Pressure	atm
9-24	16X	Blank	---
25-33	F9.4	Temperature	$^{\circ}K$ ($^{\circ}R$ if negative, in which case enthalpies below are Btu/lb)
34-38	F5.3	Unequal diffusion exponent	---
39-47	F9.3	Summation $\sum_{ie} Z_i^* h_i^T$	cal/gr (Btu/lb if temperature is entered with minus sign)
48-56	F9.3	h_{ew}	cal/gr (Btu/lb if temperature is entered with minus sign)
57-58	I2	-1 (flag signifying that this card is part of the edge gas table)	---

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
59-66	2A4	Unused, but may contain alphameric information	---
67-78	2A6	Problem identification (not read)	---
79-80	2X	UNUSED	---

Note that although the EST and ACE programs will provide a data deck using $^{\circ}\text{K}$ and cal/gr, in those rare cases in which a user wishes to supply his own deck and prefers to work in $^{\circ}\text{R}$ and Btu/lb, he may do so simply by introducing a minus sign as a flag in front of the temperature entries.

The table length is limited to 5 pressure sets (it may have only 1 pressure set) with not more than 30 nor less than 3 temperature entries in each set. The series of temperature values may be different for each pressure set. The table has been organized as a series of sections, each representing one pressure and each preceding the corresponding pressure group of the surface thermochemistry deck as described below. The temperature entries within each section must be ordered, either ascending or descending. Similarly, the pressures must be ordered either ascending or descending. (Deck generated by the EST and ACE programs will have been automatically ordered properly.) The sketch shown on the following page demonstrates the thermochemical data tables make-up.

3.1.10.3.3 Surface thermochemistry table

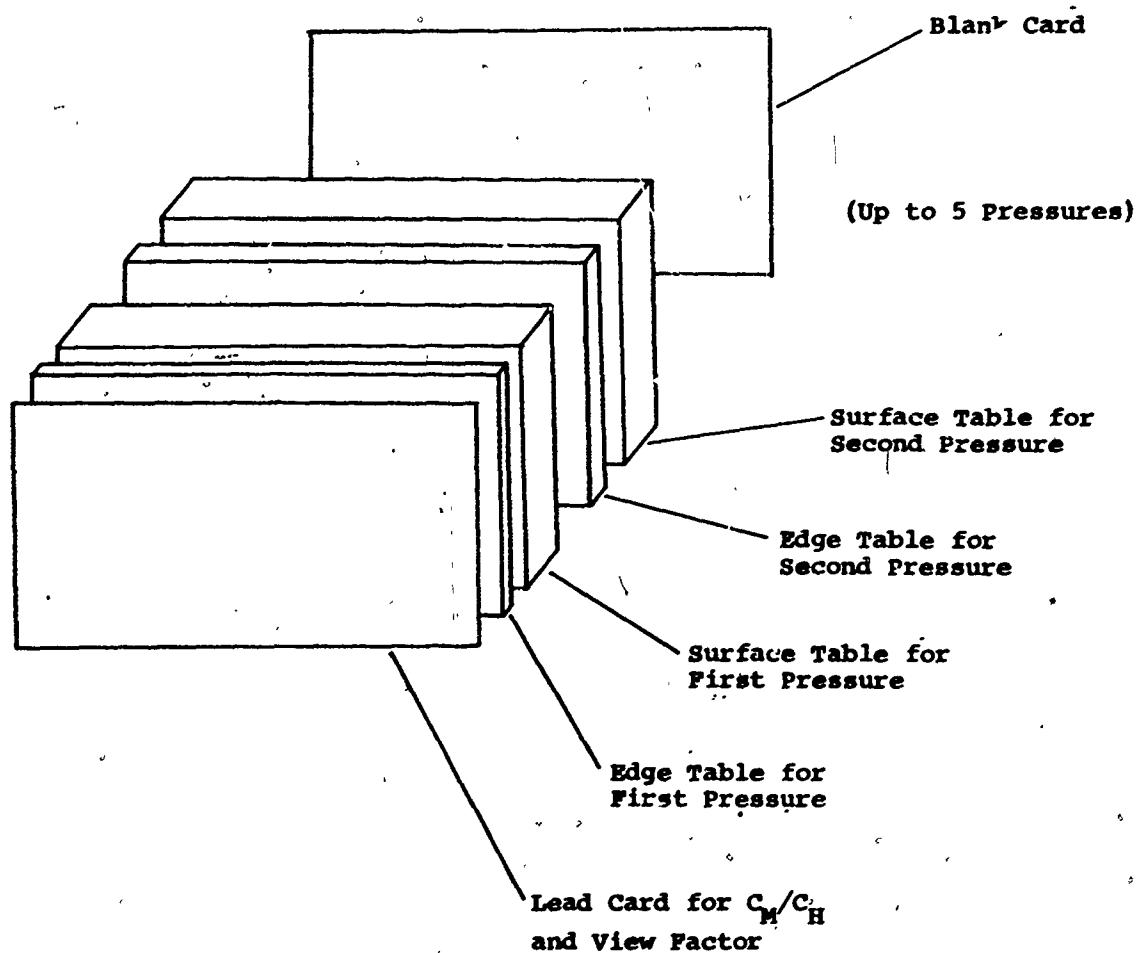
This table is comprised of a series of sections of up to 29 cards each. The sections represent one pressure and one pyrolysis gas rate. Each section consists of two subsections. The first contains the ablating cases; here the char ablation rate is the third independent variable and the surface temperature is a dependent variable. The second subsection represents surface temperatures too low for ablation; in this subsection surface temperature is the independent variable.

Thus one table has three independent variables: pressure, pyrolysis gas rate, and either surface temperature or ablation rate, depending on whether the surface temperature is high enough for ablation.

The table has either two or three dependent variables, according to whether the surface temperature is high enough for ablation. Two dependent variables always present are the summation $\sum_{i=1}^n h_i^T$ and h_w , the enthalpy of the wall gases. The third dependent variable is the surface temperature, but it is dependent only in those cases for which the surface temperature is high enough for ablation. (Otherwise, the surface temperature functions as an independent variable.)

SKETCH OF SURFACE THERMOCHEMICAL TABLE MAKE-UP

The following sketch illustrates the make-up of the surface thermochemistry table for CMA input.



The EST and ACE programs generate separate groups for each pressure, one at a time. These groups must be ordered on pressure (either ascending or descending) by the user to make up the surface thermochemistry deck. With each pressure group the pyrolysis gas rates P'_g will be ordered in descending order. Within each gas rate section, non-zero char rate entries will be grouped ahead of the zero char rate entries. The non-zero char rate entries will not be ordered in any particular way on the char rates; any necessary ordering is made automatically by the Charring Material Ablation program as it reads the data. The zero char rate entries are ordered with descending temperatures.*

(Users providing their own thermochemistry decks must ensure that the pressures and gas rates are ordered, but the ordering may be either ascending or descending in each case. Within each gas rate section, non-zero char rate entries must precede the zero char rate entries but need not be ordered. Char rates may not be duplicated in a given table. Zero char rate entries follow and must be ordered with descending temperatures. These cards are identified as zero char rate cards by a flag in columns 57-58, as described in the format specification below.)

The number of pressure groups may not exceed 5 (and may be only 1); the number of pyrolysis gas rates in each pressure group may not exceed 20 and may not be less than 2. The sequence of gas rate values must be the same in the different pressure sections. Within each gas rate group the number of char rate entries, including the zero char rate (independent surface temperature) cards, may not exceed 30 and may not be less than 2. The series of char values may be unique for each section.

(The $^{\circ}\text{R}$ -Btu/lb option described for the edge tables in Section 3.1.10.3.2 may be used for these tables also.)

The card format for the surface thermochemistry data is as follows:

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Unit</u>
1-8	F8.5	Pressure	atm
9-16	F8.5	Gas rate $\dot{m}_g / \rho_e u_e C_M = B'_g$	---
17-24	F8.5	Char rate $\dot{m}_c / \rho_e u_e C_M = B'_c$	---
25-33	F9.4	Surface temperature	$^{\circ}\text{K}$ ($^{\circ}\text{R}$ if negative in which case enthalpies be- low are Btu/lb)

* Limitations in the EST and ACE chemistry routines sometimes require that these "zero char rates" not be zero, but some small number, for example, 0.0001. This causes no difficulty in CMA.

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
34-38	F5.3	Unequal diffusion exponent	---
39-47	F9.3	Summation $\sum_i Z_i^T h_{i,w}^T$	cal/gr (Btu/lb if temperature is entered with minus sign)
48-56	F9.3	Enthalpy of wall gases h_w	cal/gr (Btu/lb if temperature is entered with minus sign)
57-58	I2	0 for assigned-temperature entries in the thermochemistry program (no ablation); > 0 for standard surface thermochemistry with ablation (temperature is dependent)	---
59-60	2X	Blank	---
61-66	A6	Chemical symbol of surface species (EST program prints such symbols arranged alphabetically and truncated from right end if necessary.)	---
67-78	2A6	Problem identification (not read)	---
79-80	I2	UNUSED	---

The ACE program can account, as one of its options, for mechanical removal or failing of candidate surface species at defined temperatures. The energy associated with this failing can be (and is) accounted for by the ACE-CMA program combination; this is accomplished by ACE by suitably modifying the h_w output term on the punched card thermochemistry table (thus h_w does not represent the enthalpy of the wall gases if failing is occurring).

The actual value of the dimensionless failing rate $B_f' = \dot{m}_f / \rho_e u_e C_M$ may or may not appear on the punched surface thermochemistry card tables, depending on whether or not the ACE user has called for the appropriate card output format. This "new format" differs from that cited above in columns 61-80:

Alternate Card Format - Surface Tables

<u>Column</u>	<u>Format</u>	<u>Data</u>	<u>Units</u>
1-60	As described above		
61-68	2A4	Chemical symbol of surface species	---
69-78	E10.3	$B_f' = \dot{m}_f / \rho_e u_e C_M$	---
79-80	2X	Blank	---

The CMA user may call for the CMA program to read these B_f^i entries and to allow for them in the blowing correction to C_{H_0} by punching a one in column 50 in the lead card for the surface thermochemistry tables, as described in Section 3.1.10.2 above.

3.1.10.3.4 Termination card

The surface thermochemistry data deck must be terminated by a single blank card. Output decks of the EST and ACE programs may not have such a card, in which case the user must supply it.

3.2 PROGRAM OUTPUT

3.2.1 Input Data (Except Surface Thermochemistry Tables)

Program output begins with an output of the input title and heading information, internal decomposition kinetic data, output interval specifications and general program constants, nodal data, material property tables, pyrolysis gas enthalpy table, and time dependent boundary conditions table.

All this output is fully labeled and is printed exactly as input by the user. Examples of these outputs are included in Section 4.

3.2.2 Surface Thermochemistry Tables

3.2.2.1 Edge Enthalpy Table

If there is an edge enthalpy table, it is output exactly as input.

3.2.2.2 Surface Thermochemistry Table

This table is output re-ordered with increasing char rates in each section and with a new computed term in place of the input enthalpy terms. For each entry in the surface equilibrium tables the program computes the quantity*

$$\left[\sum_i (Z_{ie}^* - Z_{iw}^*) h_i^{T_w} - B' h_w + \frac{\dot{m}_c h_c}{\rho_e u_e C_M} + \frac{\dot{m}_g h_g}{\rho_e u_e C_M} \right] = \frac{q_{chem}}{\rho_e u_e C_M} = \text{chem prod.}$$

and then outputs it as the dependent variable of interest in the output surface equilibrium table. This term occurs directly in the surface energy balance, Equation (9) of Section 2.4.3 above. In the output, this quantity is labeled CHEM PROD. It has the units $(\text{Btu}/\text{ft}^2\text{-sec})/(\text{lb}/\text{ft}^2\text{-sec}) = \text{Btu}/\text{lb}$ and can be thought of as the chemical energy release per pound of $\rho_e u_e C_M$, where $\rho_e u_e C_M$ can be thought of as the "scrubbing flux" or "Reynolds flux."

* If edge tables are omitted, only the last three terms are included.

In the output table, the quantity $\rho_e u_e C_M$ is abbreviated to CM.

3.2.3 Regular Output

3.2.3.1 Introduction

At each output interval, as specified by the user, the program prints out the current values of ablation rates, nodal temperatures and densities, and other supplementary information, as described below. Samples of the regular output are given in Section 4.

3.2.3.2 General Information

The first line of output shows the current values of a number of miscellaneous quantities:

Heading

TIME STEP	Total number of computational cycles (steps) required to reach the indicated value of output time. Note that the initial time is numbered as 1.
SURF ITER	Number of iterations required for the surface energy balance during the previous cycle.
PROB OPTN	Current problem option (1, 2, or 3)
SURFACE RAD (IN)	Current value of surface radius for axisymmetric geometries; current location of surface for planar geometries, measured from original location.
H WALL	Option 1: Enthalpy of frozen <u>edge</u> gases at the wall temperature. Option 2: Blank Option 3: Enthalpy of pyrolysis gases at the wall temperature
H EDGE	The input edge enthalpy as determined by linear interpolation in the functions-of-time table.
HEAT COEFF	The current value of the convective heat transfer coefficient $\rho_e u_e C_H$ as linearly interpolated in the functions-of-time table and corrected for the effect of transpiration (blowing) according to $C_H/C_{H_1} = \zeta / (e^\zeta - 1) \text{ where } \zeta = 2\lambda_m/C_{H_1} \text{ and } C_{H_1}$ is the heat transfer coefficient before being corrected for blowing; as well as for any radius ratio effect.
CH/CHO	The ratio C_H/C_{H_1} , indicates the amount of blowing correction.

3.2.3.3 Ablation Rates

The output labels are interpreted as follows:

<u>Heading</u>	<u>Data</u>
B PRIME	The parameter $B' = \dot{m}/\rho_e u_e C_M$
B PRIME G	Parameter B' based on gas flow alone: $\dot{m}_g/\rho_e u_e C_M$
M DOT CHAR	Current char removal rate \dot{m}_c , lb/ft ² sec
M DOT GAS	Current pyrolysis gas flow rate at the surface \dot{m}_g , lb/ft ² sec.
M CHAR	Total char removal up to current time, based on a unit area of the original surface, lb/ft ² .
M GAS	Total pyrolysis gas generation up to current time, based on a unit area of the original surface, lb/ft ² .

3.2.3.4 Recessions and Recession Rates

A single output line gives the current locations, as measured from the original location of the surface, of the ablating surface, the char line [defined as the line of density $\rho_c + r_c(\rho_p - \rho_c)$], and the pyrolysis line [defined as the line of density $\rho_c + r_p(\rho_p - \rho_c)$], as well as the current rates of movement of these lines. The values r_c and r_p are also printed for convenience.

3.2.3.5 Surface Energy Flux Terms

Two lines of output give the current values of the surface energy flux terms in Equation (9) of Section 2.4.3, based on one square foot of the present surface, and the integrated values of these terms based on one square foot of the original surface.

The headings and data are related as follows:

<u>Heading</u>	<u>Data</u>
CONVECTED IN	$q_{sen} = \rho_e u_e C_H (H_r - h_{e_w})^*$
RADIATED IN	$q_{rad} = \alpha_w q_{rad}$ in
RADIATED OUT	$q_{rad} = \sigma \epsilon T_w^4$ out
CHEMICAL GENERATION	q_{chem}
CONDUCTION AWAY	q_{cond}

* If edge tables are omitted, h_{e_w} is set to zero for output purposes.

3.2.3.6 Interior Energy Terms

Two lines of output show terms which describe how the input energy of q_{cond} is "accommodated" or "partitioned" in the solid material. Part of it is consumed in decomposing the plastic, part is consumed in sensible enthalpy changes of the solid, and part is "picked-up" by the pyrolysis gases as they pass through the char.

These terms are given by the energy equation (3) of Section 2.1.2 when these terms are integrated over the total extent of the ablating material. The headings and the terms are related as follows.

The pyrolysis gas pick-up represents the energy picked up by all the pyrolysis gas during its passage through the char layer. The decomposition absorption is simply the energy absorbed in isothermally decomposing the virgin plastic. The loss at the rear face is the energy passing out the back wall of the ablation material (not the back up materials). Two terms give the total rate of storage in solid materials. This quantity could in fact be represented by only one term

$$\int \rho C_p \frac{\partial T}{\partial \theta} \bigg|_y \frac{A \, dx}{A_s}$$

but it is more useful to divide into the two parts as indicated. For problems with a steady state temperature profile (in x), the "Storage in Solid" term

$$\int \rho C \frac{\partial T}{\partial \theta} \bigg|_x \frac{A \, dx}{A_s}$$

goes to zero. In general, the relative sizes of the "Storage in Solid" term and the "Convection with Solids" term indicate the nearness of the approach to a steady state.

Heading	Data
PYROLY GAS PICK UP	$-\int \dot{m}_g \frac{\partial h_g}{\partial x} \bigg _\theta \frac{dx}{A_s} = (\dot{m}_g h_g)_w + \int h_g \left(\frac{\partial \rho}{\partial \theta} \right)_y \frac{A \, dx}{A_s}$
DECOMP ABSORPTION	$-\int (h_g - \bar{h}) \left(\frac{\partial \rho}{\partial \theta} \right)_y \frac{A \, dx}{A_s}$
CONVECTION WITH SOLIDS	$-\int \dot{\rho} C_p \frac{\partial T}{\partial x} \bigg _\theta \frac{A \, dx}{A_s}$

STORAGE IN
SOLID

$$\int \frac{1}{\rho C_p} \frac{\partial T}{\partial \theta} \bigg|_x \frac{A}{A_s} dx$$

LOSS AT REAR
FACE

$$-k \frac{A_{BW}}{A_s} \left[\frac{\partial T}{\partial x} \right]_{\theta} \bigg|_{BW}$$

The second line of output gives time-integrated total values of these energy rate terms, based on one square foot of the original surface.

3.2.3.7 Nodal Data

This output gives the current temperature, density and enthalpy* of all the nodes, as well as material number specifications, where material number 1 designates main material virgin plastic, defined as having a density equal to or greater than $(\rho_p - 0.1 \text{ lb/ft}^3)$, material number 2 designates main material char, defined as having a density equal to or less than $(\rho_c + 0.01 \text{ lb/ft}^3)$, material number 0 designates reacting char-plastic mixture with intermediate density, numbers 21-31 designate charring back-up material numbers according to the table of Section 3.1.6, and material numbers 3-10 designate non-charring back-up materials.

3.2.3.8 Char Swell Information

If the user has called for char swell corrections (Sections 2.4.3.4 and 3.1.10.2), two lines indicate the net surface recession and current surface recession rate as affected by the char swell effect.

3.2.4 Thermocouple and Isotherm Output

3.2.4.1 Listed Output

If thermocouple and/or isotherm output have been called for, this data will be listed at the end of the regular output, giving thermocouple temperatures in degrees Rankine and isotherm locations in inches from the location of the original surface.

In both cases the output data are determined by a curve fitting routine which extrapolates beyond the physical boundaries of the system, so that the user must himself detect when thermocouples have ablated away and lost their meaning and when isotherms are fictitiously found outside the material boundaries.

* Nodal thermal conductivity may be output instead of enthalpy. The relevant flag punch for conductivity is in column 60 of the "back wall conditions card" described in Section 3.1.6 above.

3.2.4.2 Punched Output

If punched output of thermocouple and isotherm data is called for as described in Section 3.1.3 above, the data will be punched on cards in the order: time, surface temperature, thermocouple temperatures (in the input order), isotherm depths (in the input order). The format is (8F10.4/10X7F10.4).

3.3 DUMPS

3.3.1 Introduction

To prevent the execution of computations that are wasteful or probably erroneous, the program provides two emergency stops with dumps of diagnostic information.

3.3.2 Too-Small-Time-Step Dump

One such dump occurs if the program selects a time step as small as 10^{-6} seconds. Computation ceases and the program prints out in a single line values of the current time (which will, of course, not in general correspond to a regular output time), the time increment Δt , the previous time increment for comparison, the amount of problem time from the previous time-table double entry (shift of option) or discontinuity, change in surface temperature during last computation step, the critical recession distance parameter (equal to one-fifth of the thickness of the first node or one-tenth of the minimum allowable last node thickness, whichever is smaller (Δt is restricted so that recession during the computation step will not exceed this amount), and the surface recession rate (ft/sec) computed most recently.

Once this data has been output, the program sets the problem time equal to the final time, thus forcing an output of all the current values of the standard output quantities, followed by a termination of computation.

3.3.3 Too-Many-Surface-Iterations Dump

The program allows 51 iterations to find an acceptable surface energy balance. If a balance has not been obtained after 51 iterations, the program writes the diagnostic message "Iteration.Stop" and a block of diagnostic data. Since stops of this kind are complex in nature, and generally involve the surface thermochemistry tables data deck, the dump data must usually be communicated to the program authors for analysis.

3.3.4 Unacceptable-Surface-Thermochemistry-Table Stop

A series of checks built into the input routine serve to detect common errors in the make-up of the surface thermochemistry tables. Discovery of an error stops the reading process and the program prints out a single line:

Bad Surface Equilibrium Table of Type -

Five error types are detected as follows:

Type

- | | |
|---|---|
| 0 | Current section of independent temperature entries (no ablation) is not in descending order in temperature |
| 1 | Char rate in no-ablation subsection has been set greater than a char rate in the ablation subsection. Although the "zero-char-rate" can differ from zero, they must not exceed an actual ablation rate entry. |
| 2 | Edge table has been omitted even though the diffusion coefficients are not equal (unequal diffusion exponent $\neq 0$). |
| 3 | Edge table has been omitted even though $C_M/C_H \neq 1$. |
| 4 | Inconsistent unequal diffusion exponent (this must be uniform for all tables). |
| 5 | Have called for radius ratio and/or burn rate exponent correction to C_{H_2O} although this is an internal radius geometry. |

3.3.5 Sense Switch Diagnostic Dumps

Sense switch calls built into the Charring Material Ablation Code provide diagnostic dumps of certain data during program execution. Usually such dumps are of interest only to the program authors, although for reference these dumps are summarized here:

Sense Switches

Dump when On

- | | |
|---|---|
| 1 | Writes another version of each surface thermochemistry table immediately after the regular output of this table; presents final forms of energy terms as actually used in surface energy balance computations; useful for analysis of surface energy balance failures |
| 3 | Dumps nodal numbers of decomposing back-ups, after regular output of input data, for checking purposes; also dumps at each standard output time various density and pyrolysis rates for nodes in charring back-up materials |

- | | |
|---|--|
| 4 | Supplies standard output for each time step, regardless of formal output time specifications |
| 5 | Outputs diagnostic heat conduction quantities in charring back-ups each time step, only used for detailed analysis |

3.4 MISCELLANEOUS

3.4.1 Running Time

Computation time depends, of course, on the problem being computed, but typical computations for charring materials run roughly in real time on the IBM 7090/7094. Appendix B presents a method for estimating run times.

3.4.2 Tape Requirements

Internal program assignments are as follows:

- Tape Unit 3: Scratch used during execution
- Tape Unit 5: Input
- Tape Unit 6: Output
- Tape Unit 7: Punch

3.4.3 Fortran Deck Make-Up

The Charring Material Ablation program source deck is in Fortran IV (or Fortran 63).

The program consists of the following units:

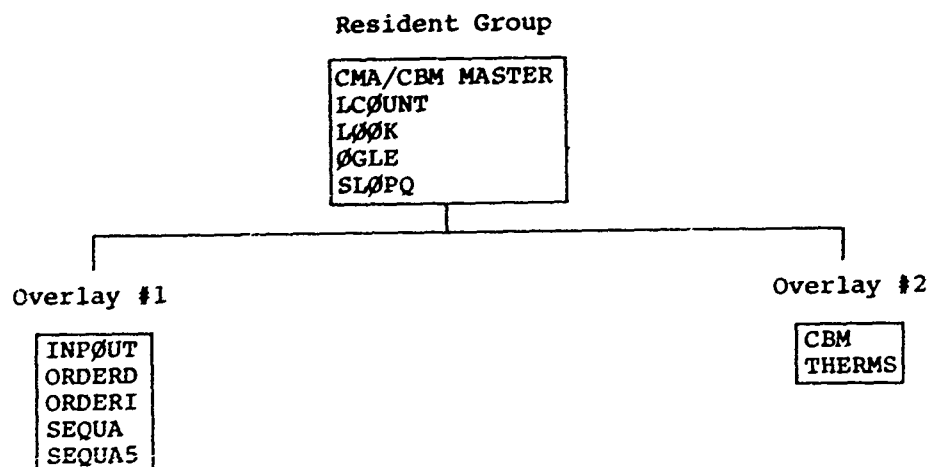
1. Main Program
Drives INPØUT and CBM routines
2. Subroutine CBM
Computes all time dependent results
3. Subroutine* INPØUT
Reads in all input data and outputs same data in front of standard computed output
4. Subroutine LCØUNT
Counts lines, turns and numbers pages
5. Subroutine LØØK
Table look-up with linear interpolation
6. Subroutine SLØPQ
Quadratic curve fit and slope finder
7. Subroutine ØGLE
Table look-up with cubic curve fit

8. Subroutine ØRDERD
Ordering routine
9. Subroutine ØDERI
Integer Array Ordering Routine
10. Subroutine SEQUA
Orders according to results of ØRDERD
11. Subroutine SEQUA5
Orders up to 5 Dependent Variable Arrays according to results of ØRDERD

3.4.4 Storage Requirements

With "standard" dimensions on subscripted variables, the Charring Material Ablation program generally fits within the 32,000 words of CDC and Univac equipment. The program will not fit the 32,000 words of the IBM 7090/7094 machine by several thousand words. Simple dimension cutting is usually adequate to effect a fit in most cases. In others, a special overlay version of the code exists, although only minor improvements can be realized in this way since most storage requirements are for data.

The first level overlay structure has the following form:



3.4.5 Stacking of Jobs

A series of data decks representing different problems may be stacked for sequential computation.

SECTION 4

SAMPLE PROBLEMS

This section presents input listings and selected output page listings for four sample problems illustrating various features of the CMA Version 3 code. The following table summarizes the essential features of each problem. As it happens, these examples are all from rocket nozzle technology, although the CMA code is equally useful for ablating exterior heat shield analysis, various combustion problems, and, of course, simple transient heat conduction studies.

CMA/CDM SAMPLE PROBLEMS

Sample Problem	Description	Comment
No. 1	Transient thermal response at the throat location of a carbon phenolic nozzle exposed to an aluminized solid propellant. Nodal network includes steel shell back-up. Heat transfer coefficient is corrected for radius change and burning rate as a function of time.	This problem shows the effect of burning rate correction on the convective heat transfer coefficient. In addition, the input of f-functions is demonstrated although only a linear variation is used. Finally, since no decomposing back up materials are present, this problem shows that the CMA/CDM code will do all problems that the CMA, Version 2 code could do.
No. 2	Identical surface boundary conditions as Sample Problem No. 1, but the nodal network contains seven silica phenolic nodes which decompose when sufficiently heated.	This problem demonstrates the input and output for the CMA/CDM solution of a nodal system containing a decomposing back-up material. Also the temperatures of three thermocouples and the depths of two isotherms are computed and output, and the nodal thermal conductivity is output instead of enthalpy.
No. 3	Identical surface boundary conditions and nodal network as Sample Problem No. 2, but the radius in this problem is corrected for char swell.	The effect of char swell on the predicted recession is demonstrated in this problem.
No. 4	Identical to Sample Problem No. 2, except that the "fissure" model is utilized to describe pyrolysis gas terms. (This requires a change in the surface thermochemistry model and the pyrolysis gas enthalpy table.)	The effect of "fissure" model on the prediction is demonstrated.

CMA/CHN ANALYSIS AT ABLATIVE THROAT OF A SOLID PROPELLANT ROCKET MOTOR
 THROAT SURFACE IS CARBON PHENOLIC AT A 30 DEGREE LAYUP ANGLE. P=29 ATM
 HEAT TRANSFER COEFFICIENT CORRECTED FOR BLOWING RATE EXP. SAMPLE NO. 1

1	20.25	0.0	1.400+04	1.00	1.740+04	1000.0
2	40.75	32.40	1.400+04	1.00	1.740+04	1000.0
3	90.50	90.50	0.0	0.0	0.0	00000.0
4	0.0	120.0	0.5	2.0	5.0	1.0
5	2.0	10.0	0.04	-376.5	0.0	0.0
6	1.0	1.04	1.4			
7	531.0	1000.0				
8	530.0		0.020	1.15		
9	530.0		0.040			
10	530.0		0.040			
11	530.0		0.040			
12	530.0		0.060			
13	530.0		0.100			
14	530.0		0.100			
15	530.0		0.100			
16	530.0		0.1			
17	530.0		0.1			
18	530.0		0.150			
19	530.0		0.150			
20	530.0		0.2			
21	530.0		0.2			
22	530.0		0.250			
23	530.0		0.250			
24	0.0	0.0	532.0			
25	530.0	0.210	1.400+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
26	400.0	0.340	2.110+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
27	1160.0	0.340	2.470+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
28	1500.0	0.472	2.470+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
29	2000.0	0.484	2.470+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
30	3000.0	0.493	2.470+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
31	4000.0	0.494	2.470+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
32	5000.0	0.500	2.470+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
33	6000.0	0.500	2.470+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
34	530.0	0.210	2.470+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
35	1000.0	0.470	2.530+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
36	1500.0	0.472	2.540+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
37	2000.0	0.484	2.540+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
38	3000.0	0.493	2.540+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
39	4000.0	0.494	2.540+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
40	5000.0	0.500	2.540+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
41	6000.0	0.500	2.540+04	0.630	444926	(VIRGIN-60 DEG LAYUP)
42	440.00	0.110	0.000+04			
43	5300.0	0.110	0.000+04			
44	0.0	0.0	0.0			
45	0.0	0.0	0.0			
46	0.0	0.0	0.0			
47	0.0	0.0	0.0			
48	0.0	0.0	0.0			
49	0.0	0.0	0.0			
50	0.0	0.0	0.0			
51	0.0	0.0	0.0			
52	0.0	0.0	0.0			
53	0.0	0.0	0.0			
54	0.0	0.0	0.0			
55	0.0	0.0	0.0			
56	0.0	0.0	0.0			
57	0.0	0.0	0.0			
58	0.0	0.0	0.0			
59	0.0	0.0	0.0			
60	0.0	0.0	0.0			
61	0.0	0.0	0.0			
62	0.0	0.0	0.0			
63	0.0	0.0	0.0			
64	0.0	0.0	0.0			
65	0.0	0.0	0.0			
66	0.0	0.0	0.0			
67	0.0	0.0	0.0			
68	0.0	0.0	0.0			
69	0.0	0.0	0.0			
70	0.0	0.0	0.0			
71	0.0	0.0	0.0			
72	0.0	0.0	0.0			
73	0.0	0.0	0.0			
74	0.0	0.0	0.0			
75	0.0	0.0	0.0			
76	0.0	0.0	0.0			
77	0.0	0.0	0.0			
78	0.0	0.0	0.0			
79	0.0	0.0	0.0			
80	0.0	0.0	0.0			
81	0.0	0.0	0.0			
82	0.0	0.0	0.0			
83	0.0	0.0	0.0			
84	0.0	0.0	0.0			
85	0.0	0.0	0.0			
86	0.0	0.0	0.0			
87	0.0	0.0	0.0			
88	0.0	0.0	0.0			
89	0.0	0.0	0.0			
90	0.0	0.0	0.0			
91	0.0	0.0	0.0			
92	0.0	0.0	0.0			
93	0.0	0.0	0.0			
94	0.0	0.0	0.0			
95	0.0	0.0	0.0			
96	0.0	0.0	0.0			
97	0.0	0.0	0.0			
98	0.0	0.0	0.0			
99	0.0	0.0	0.0			
100	0.0	0.0	0.0			

INPUT, SAMPLE PROBLEM 1

29.20000	0.10000	0.000101095.31170.	-884.688	-884.688	1	C*	0.
29.20000	0.10000	0.000101000.00000.	-1045.954	-1045.954	0	AL203*	0.
29.20000	0.10000	0.00010 500.00000.	-1374.827	-1374.827	0	AL203*	0.
29.20000	0.06000	0.35003446.34560.	1674.303	1674.303	1	C*	0.
29.20000	0.06000	0.200001191.95550.	1111.021	1111.021	1	C*	0.
29.20000	0.06000	0.150003028.23220.	859.936	859.936	1	C*	0.
29.20000	0.06000	0.100002731.58620.	531.322	531.322	1	C*	0.
29.20000	0.06000	0.080002506.35480.	344.891	344.891	1	C*	0.
29.20000	0.06000	0.070002314.54540.	211.524	211.524	1	C*	0.
29.20000	0.06000	0.065002151.65580.	109.606	109.606	1	C*	0.
29.20000	0.06000	0.060001325.71120.	-461.918	-461.918	1	C*	0.
29.20000	0.06000	0.050001241.34840.	-583.801	-583.801	1	C*	0.
29.20000	0.06000	0.040001151.88170.	-758.859	-758.859	1	C*	0.
29.20000	0.06000	0.030101016.34140.	-1033.389	-1033.389	1	C*	0.
29.20000	0.06000	0.000101000.00000.	-1061.854	-1061.854	0	AL203*	0.
29.20000	0.06000	0.00010 500.00000.	-1384.661	-1384.661	0	AL203*	0.
29.20000	0.03500	0.350003446.88240.	1645.678	1645.678	1	C*	0.
29.20000	0.03500	0.200003179.22710.	1063.164	1063.164	1	C*	0.
29.20000	0.03500	0.150002990.68670.	799.242	799.242	1	C*	0.
29.20000	0.03500	0.100002646.98070.	448.337	448.337	1	C*	0.
29.20000	0.03500	0.080002326.98750.	286.774	286.774	1	C*	0.
29.20000	0.03500	0.075002166.44010.	186.992	186.992	1	C*	0.
29.20000	0.03500	0.070001337.17750.	-452.619	-452.619	1	C*	0.
29.20000	0.03500	0.065001245.63380.	-578.878	-578.878	1	C*	0.
29.20000	0.03500	0.050001194.01830.	-678.321	-678.321	1	C*	0.
29.20000	0.03500	0.00010 899.26350.	-1195.571	-1195.571	1	C*	0.
29.20000	0.03500	0.00010 500.00000.	-1391.193	-1391.193	0	C*	0.
29.20000	0.02000	0.350003446.28720.	1628.023	1628.023	1	C*	0.
29.20000	0.02000	0.200003170.86380.	1033.320	1033.320	1	C*	0.
29.20000	0.02000	0.150002978.39280.	768.889	768.889	1	C*	0.
29.20000	0.02000	0.100002582.78380.	378.825	378.825	1	C*	0.
29.20000	0.02000	0.080002129.85570.	78.164	78.164	1	C*	0.
29.20000	0.02000	0.075001328.44640.	-465.197	-465.197	1	C*	0.
29.20000	0.02000	0.070001275.99810.	-533.272	-533.272	1	C*	0.
29.20000	0.02000	0.060001215.23460.	-632.586	-632.586	1	C*	0.
29.20000	0.02000	0.050001170.94980.	-718.460	-718.460	1	C*	0.
29.20000	0.02000	0.00010 685.98190.	-1358.252	-1358.252	1	C*	0.
29.20000	0.02000	0.00010 500.00000.	-1395.265	-1395.265	0	AL203*	0.
29.20000	0.00010	0.350003450.88590.	1604.023	1604.023	1	C*	0.
29.20000	0.00010	0.200001154.75570.	992.289	992.289	1	C*	0.
29.20000	0.00010	0.150002944.10120.	787.221	787.221	1	C*	0.
29.20000	0.00010	0.100002472.02610.	284.658	284.658	1	C*	0.
29.20000	0.00010	0.092502306.33350.	175.096	175.096	1	C*	0.
29.20000	0.00010	0.087502119.58270.	62.729	62.729	1	C*	0.
29.20000	0.00010	0.085001914.41820.	-56.221	-56.221	1	C*	0.
29.20000	0.00010	0.082501330.25080.	-466.518	-466.518	1	C*	0.
29.20000	0.00010	0.080001299.59880.	-583.670	-583.670	1	C*	0.
29.20000	0.00010	0.080001181.20380.	-698.886	-698.886	1	C*	0.
29.20000	0.00010	0.050001140.60580.	-788.959	-788.959	1	C*	0.
29.20000	0.00010	0.00010 680.47750.	-1384.243	-1384.243	1	C*	0.
29.20000	0.00010	0.00010 500.00000.	-1400.855	-1400.855	0	AL203*	0.

INPUT, SAMPLE PROBLEM 1 (CONCLUDED)

CH/CHO = PHI/(EXP(PHI)-1.) WHERE PHI = 2.*BHP*W DOT/CHO. RRP IN TABLE

MATERIAL NO. 2		DENSITY = 70.864 LB/CU FT		SENSIBLE ENTHALPY		EMISSIVITY	
TEMPERATURE	SPECIFIC HEAT	CONDUCTIVITY	(BTU/FT-SEC-DEG)	(BTU/LB)			
(DEG R)	(BTU/LB-DEG)	(BTU/FT-SEC-DEG)					
530.00	.2100	.0002470		-1.92		.6300	
1000.00	.4300	.0005330		148.48		.6300	
1500.00	.4720	.0005580		373.98		.6300	
2000.00	.4840	.0005840		612.98		.6300	
3000.00	.4930	.0007190		1101.48		.6300	
4000.00	.4980	.0013400		1596.98		.6300	
5000.00	.5000	.0020000		2095.98		.6300	
6000.00	.5000	.0027500		2595.98		.6300	
MATERIAL NO. 3		DENSITY = 486.000 LB/CU FT		CONDUCTIVITY			
TEMPERATURE	SPECIFIC HEAT	CONDUCTIVITY	(BTU/FT-SEC-DEG)				
(DEG R)	(BTU/LB-DEG)	(BTU/FT-SEC-DEG)					
500.00	.1100	.0009400					
5000.00	.1100	.0009400					

TABLES OF OPTIONAL MASS-FRACTION FUNCTIONS FOR THERMAL CONDUCTIVITY
K = F1(X)*KP + F2(X)*KC

F-FUNCTION TABLE NO. 1 ASSIGNED TO
MAIN MATERIAL

X	F1(X)	F2(X)
.0000	.0000	1.0000
1.0000	1.0000	.0000

---RESIN DECOMPOSITION GAS SENSIBLE ENTHALPY---

TEMPERATURE (DEG R)	900.00	1800.00	2700.00	3600.00	4500.00
ENTHALPY (BTU/LB)	-1782.00	-930.20	195.00	2289.00	3600.00
TEMPERATURE (DEG R)	5400.00	6300.00			
ENTHALPY (BTU/LB)	4696.00	6132.00			

---TIME DEPENDENT BOUNDARY CONDITIONS---

TIME (SEC)	PROB OPTN	RECOVERY ENTHALPY (BTU/LB)	RADIATION HEAT RATE (BTU/SQ FT-SECOND)	HEAT COEFF (LB/SQ FT-SECOND)	PRESSURE (ATM)	BLOWING REDUCTION PARAMETER
.00	1	1947.00	904.00	.8588	29.20000	.375
10.00	1	1947.00	904.00	.7238	29.20000	.375
60.00	1	1947.00	904.00	.7238	29.20000	.375
TIME (SEC)	PROB OPTN	VIEW FACTOR	RADIATION HEAT RATE (BTU/SQ FT-SECOND)			
60.00	3	.05	.00			
120.00	3	.05	.00			

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

---SURFACE EQUILIBRIUM DATA---

RATIO OF MASS TO HEAT TRANSFER COEFFICIENTS = .002
UNEQUAL DIFFUSION EXPONENT = .000
NOMINAL SURFACE VIEW FACTOR = 1.000 (OPTION 1)
FISSEUR MODEL NOT USED FOR GAS TERMS
HEAT TRANSFER COEFFICIENT MULTIPLIED BY INITIAL RATE CURRENT ORDER
WHERE EA = (1.8-2M)/(1.1-M) AND N IS THE BURNING RATE EXPONENT.
IN THIS PROBLEM N HAS BEEN SET EQUAL TO .02500
NO CHAR SHELL CONNECTION ON SURFACE NECESSARY

* = 29.2000 ATM

TEMP (DEG R)	EDGE ENTH (DEG R)	TEMP (DEG R)	EDGE ENTH (DEG R)	TEMP (DEG R)	EDGE ENTH (DEG R)
600.00	1645.39	3400.00	365.80	900.00	-729.04
500.00	1289.57	2700.00	-37.37		
4500.00	781.41	1800.00	-410.44		

M-DOOT-GAS/CH = .5000 PRESSURE = 29.2000 ATM					
TEMP (DEG R)	M-DOOT-CHAR/CH	CHEM-PROD (BTU/LB)	SURFACE (BTU/LB)	TEMP (DEG R)	M-DOOT-CHAR/CH
900.00	.0001	1824.41	5858.44	900.00	.0000
1800.00	.0001	1639.89	5457.38	1800.00	.0000
2700.00	.0001	137.70	5938.69	2700.00	.0000
3600.00	.0001	702.38	6175.30	3600.00	.0000
4500.00	.0001	731.68	6175.30	4500.00	.0000
5200.00	.0001	667.30	6175.30	5200.00	.0000

M-DOOT-GAS/CH = .2000 PRESSURE = 29.2000 ATM

TEMP (DEG R)	M-DOOT-CHAR/CH	CHEM-PROD (BTU/LB)	SURFACE (BTU/LB)	TEMP (DEG R)	M-DOOT-CHAR/CH
900.00	.0001	1837.53	4544.43	900.00	.0300
1800.00	.0001	1584.73	4685.80	1800.00	.0500
2250.05	.0031	892.01	5366.24	2250.05	.1000
2310.10	.0030	817.04	5645.99	2310.10	.1500
3510.08	.0075	661.57	5637.59	3510.08	.2000
3800.19	.0100	677.63	6190.23	3800.19	.3500

M-DOOT-GAS/CH = .1000 PRESSURE = 29.2000 ATM

TEMP (DEG R)	M-DOOT-CHAR/CH	CHEM-PROD (BTU/LB)	SURFACE (BTU/LB)	TEMP (DEG R)	M-DOOT-CHAR/CH
900.00	.0001	1815.18	3906.72	900.00	.0500
1800.00	.0001	1561.78	5095.08	1800.00	.1000
1971.58	.0001	1322.83	5521.30	1971.58	.1500
2040.69	.0100	1222.21	5777.16	2040.69	.2000
2180.48	.0300	998.02	6198.98	2180.48	.3500

OUTPUT SAMPLE PROBLEM 1 (CONTINUED)

M-DOT-OAS/CH = .0600 PRESSURE = 29.2000 ATM									
TEMP	M-DOT-CHAR/CM	CHEN-PROD	SURFACE	TEMP	M-DOT-CHAR/CM	CHEN-PROD	SURFACE	TEMP	M-DOT-CHAR/CM
(DEG R)		(BTU/LB)	SPECIES	(DEG R)		(BTU/LB)	SPECIES	(DEG R)	
900.00	.0001	1808.23	C*	4195.18	.0700	444.09	C*	4195.18	.0700
1800.00	.0001	1832.48	C*	4317.71	.1000	382.84	C*	4317.71	.1000
1833.01	.0001	1817.26	C*	4340.82	.1500	324.01	C*	4340.82	.1500
2073.39	.0000	1841.07	C*	5745.82	.2000	-334.03	C*	5745.82	.2000
2338.48	.0000	793.57	C*	6203.42	.3500	-1347.11	C*	6203.42	.3500
3872.48	.0030	528.85	C*						
M-DOT-OAS/CH = .0350 PRESSURE = 29.2000 ATM									
TEMP	M-DOT-CHAR/CM	CHEN-PROD	SURFACE	TEMP	M-DOT-CHAR/CM	CHEN-PROD	SURFACE	TEMP	M-DOT-CHAR/CM
(DEG R)		(BTU/LB)	SPECIES	(DEG R)		(BTU/LB)	SPECIES	(DEG R)	
900.00	.0001	1800.64	C*	4488.58	.0800	444.24	C*	4488.58	.0800
1618.67	.0001	1702.88	C*	4764.57	.1000	341.78	C*	4764.57	.1000
2150.85	.0500	1057.88	C*	5397.49	.1500	12.95	C*	5397.49	.1500
2241.96	.0500	938.26	C*	5722.61	.2000	-324.87	C*	5722.61	.2000
2408.42	.0700	786.01	C*	6208.55	.3500	-1348.12	C*	6208.55	.3500
3899.59	.0750	497.60	C*						
M-DOT-OAS/CH = .0200 PRESSURE = 29.2000 ATM									
TEMP	M-DOT-CHAR/CM	CHEN-PROD	SURFACE	TEMP	M-DOT-CHAR/CM	CHEN-PROD	SURFACE	TEMP	M-DOT-CHAR/CM
(DEG R)		(BTU/LB)	SPECIES	(DEG R)		(BTU/LB)	SPECIES	(DEG R)	
900.00	.0001	1797.29	C*	3833.74	.0800	490.84	C*	3833.74	.0800
1238.77	.0001	1428.56	C*	4449.01	.1000	355.43	C*	4449.01	.1000
2107.71	.0500	1114.58	C*	5341.11	.1500	23.04	C*	5341.11	.1500
2187.42	.0600	1004.81	C*	5707.55	.2000	-317.56	C*	5707.55	.2000
2296.80	.0700	881.02	C*	6208.57	.3500	-1348.75	C*	6208.57	.3500
2391.20	.0750	801.56	C*						
M-DOT-OAS/CH = .0001 PRESSURE = 29.2000 ATM									
TEMP	M-DOT-CHAR/CM	CHEN-PROD	SURFACE	TEMP	M-DOT-CHAR/CM	CHEN-PROD	SURFACE	TEMP	M-DOT-CHAR/CM
(DEG R)		(BTU/LB)	SPECIES	(DEG R)		(BTU/LB)	SPECIES	(DEG R)	
900.00	.0001	1792.84	C*	3815.25	.0875	472.84	C*	3815.25	.0875
1080.86	.0001	1820.09	C*	4151.40	.0925	527.21	C*	4151.40	.0925
2053.09	.0500	1193.91	C*	4449.85	.1000	376.57	C*	4449.85	.1000
2128.17	.0600	1069.47	C*	5300.78	.1500	-307.97	C*	5300.78	.1500
2336.26	.0800	805.10	C*	6211.45	.3500	-1349.69	C*	6211.45	.3500
2394.95	.0825	517.23	C*						

-----OUTPUT-----									
TIME	SURF	PROB	SURFACE	M WALL	M EDGE	HEAT CONDUCT	CH/CM	TIME	SURF
STEP	ITER	OPTN	RAD (IN)	(BTU/LB)	(BTU/LB)	(LB/50 FT-SEC)		STEP	ITER
1	0	1	1.1500	.00	1941.00	.8586	.00000	1	0
---ABLATION RATES---									
M PRIME	B PRIME	G	M DOT	CHAR	M DOT	OAS	M CHAR	M GAS	
.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
---RECESSIONS/RECESSION RATES---									
(IN)	CHAM	(IN/SEC)		CHAM	(IN/SEC)		PHOLYSIS	(IN/SEC)	
.00000000	.00000000	.00000000	.00000000	.00000000	.00000000	.00000000	.00000000	.00000000	.00000000
---SURFACE ENERGY FLUX TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
CONDUCTED	IN	OUT	IN	OUT	IN	OUT	CONVECTION	AWAY	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
RATE	TOTAL								
.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/50 FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/50 FT SURFACE-SEC)									
PYROL	GAS	PICK UP	ABSORPTION	CONVECTION	STORAGE	LOSS AT	HEAR	FACE	
.000	.000	.000	.000	.000	.000	.000	.		

TIME	SURF	PHOW	SURFACE	W. WALL	M. EDGE	HEAT CONVECT	CH/CM
SYSTEM	ITEM	OPTM	RAD	IN	(BTU/LM)	(BTU/LM)	(LM/50 FT-SEC)
50	4	1	1.1567		1.17-95	2.967-04	.7744
---ABSLATION RATES---							
W PRIME	B PRIME	O	M OUT	CHAR	M OUT	O/S	M WAS
.64732	.11462			.063301	.054677		.092867
---RELESSIONS/RECLINATION RATES---							
SURFACE				CHAM	(LM/50 FT-SEC)		
.00672317				.0107193	.01566667	.017208	PHOLYSIS (.98)
---SURFACE ENERGY FLUX TERMS---							
CURRENT RATES (BTU/50 FT				UNSAFE-SEC)			
AND INTEGRATED VALUES (BTU/CM10				50 FT)			
CONVECTED	IN	RADIATED	OUT	GENERATION	CHEMICAL	CONDUCTION	
.578-03	.370-03	.261-03		.298-02		.918-03	
TOTAL	.730-03	.971-03	.218-03		.1117-03		.120-04
---INTERIOR ENERGY TERMS---							
CURRENT RATES (BTU/50 FT				UNSAFE-SEC)			
AND INTEGRATED VALUES (BTU/CM10				50 FT)			
CONVECT	IN	CONVECTION	STORAGE	IN SOLID			
.289-03	.373-02	.785-02	.321-03				
TOTAL	.321-03	.103-03	.970-02	.672-03			
---TEMP DENSITY ENTHALPY (BTU/LM)							
MODE MAT	TEMP	DENSITY	ENTHALPY	MODE MAT	TEMP	DENSITY	ENTHALPY
0	5417-40	81	2992-89	9	530-00	89-362	378-21
1	2981-27	74-832	846-80	10	530-00	89-362	378-21
2	1228-87	68-359	135-28	11	530-00	89-362	378-21
3	691-99	64-362	-132-04	12	530-00	89-362	378-21
4	558-71	60-162	-371-74	13	530-00	89-362	378-21
5	531-21	60-162	-378-20	14	530-00	89-362	378-21
6	530-08	89-362	-378-20	15	530-00	89-362	378-21
7	530-08	89-362	-378-21	16	530-00	89-362	378-21
8	530-00	89-362	-378-21	17	530-00	89-362	378-21
9	530-00	89-362	-378-21	18	530-00	89-362	378-21
10	530-00	89-362	-378-21	19	530-00	89-362	378-21
11	530-00	89-362	-378-21	20	530-00	89-362	378-21
12	530-00	89-362	-378-21	21	530-00	89-362	378-21
13	530-00	89-362	-378-21	22	530-00	89-362	378-21
14	530-00	89-362	-378-21	23	530-00	89-362	378-21
15	530-00	89-362	-378-21	24	530-00	89-362	378-21
16	530-00	89-362	-378-21	25	530-00	89-362	378-21
17	530-00	89-362	-378-21	26	530-00	89-362	378-21
18	530-00	89-362	-378-21	27	530-00	89-362	378-21
19	530-00	89-362	-378-21	28	530-00	89-362	378-21
20	530-00	89-362	-378-21	29	530-00	89-362	378-21
21	530-00	89-362	-378-21	30	530-00	89-362	378-21
22	530-00	89-362	-378-21	31	530-00	89-362	378-21
23	530-00	89-362	-378-21	32	530-00	89-362	378-21
24	530-00	89-362	-378-21	33	530-00	89-362	378-21
25	530-00	89-362	-378-21	34	530-00	89-362	378-21
26	530-00	89-362	-378-21	35	530-00	89-362	378-21
27	530-00	89-362	-378-21	36	530-00	89-362	378-21
28	530-00	89-362	-378-21	37	530-00	89-362	378-21
29	530-00	89-362	-378-21	38	530-00	89-362	378-21
30	530-00	89-362	-378-21	39	530-00	89-362	378-21
31	530-00	89-362	-378-21	40	530-00	89-362	378-21
32	530-00	89-362	-378-21	41	530-00	89-362	378-21
33	530-00	89-362	-378-21	42	530-00	89-362	378-21
34	530-00	89-362	-378-21	43	530-00	89-362	378-21
35	530-00	89-362	-378-21	44	530-00	89-362	378-21
36	530-00	89-362	-378-21	45	530-00	89-362	378-21
37	530-00	89-362	-378-21	46	530-00	89-362	378-21
38	530-00	89-362	-378-21	47	530-00	89-362	378-21
39	530-00	89-362	-378-21	48	530-00	89-362	378-21
40	530-00	89-362	-378-21	49	530-00	89-362	378-21
41	530-00	89-362	-378-21	50	530-00	89-362	378-21
42	530-00	89-362	-378-21	51	530-00	89-362	378-21
43	530-00	89-362	-378-21	52	530-00	89-362	378-21
44	530-00	89-362	-378-21	53	530-00	89-362	378-21
45	530-00	89-362	-378-21	54	530-00	89-362	378-21
46	530-00	89-362	-378-21	55	530-00	89-362	378-21
47	530-00	89-362	-378-21	56	530-00	89-362	378-21
48	530-00	89-362	-378-21	57	530-00	89-362	378-21
49	530-00	89-362	-378-21	58	530-00	89-362	378-21
50	530-00	89-362	-378-21	59	530-00	89-362	378-21
51	530-00	89-362	-378-21	60	530-00	89-362	378-21
52	530-00	89-362	-378-21	61	530-00	89-362	378-21
53	530-00	89-362	-378-21	62	530-00	89-362	378-21
54	530-00	89-362	-378-21	63	530-00	89-362	378-21
55	530-00	89-362	-378-21	64	530-00	89-362	378-21
56	530-00	89-362	-378-21	65	530-00	89-362	378-21
57	530-00	89-362	-378-21	66	530-00	89-362	378-21
58	530-00	89-362	-378-21	67	530-00	89-362	378-21
59	530-00	89-362	-378-21	68	530-00	89-362	378-21
60	530-00	89-362	-378-21	69	530-00	89-362	378-21
61	530-00	89-362	-378-21	70	530-00	89-362	378-21
62	530-00	89-362	-378-21	71	530-00	89-362	378-21
63	530-00	89-362	-378-21	72	530-00	89-362	378-21
64	530-00	89-362	-378-21	73	530-00	89-362	378-21
65	530-00	89-362	-378-21	74	530-00	89-362	378-21
66	530-00	89-362	-378-21	75	530-00	89-362	378-21
67	530-00	89-362	-378-21	76	530-00	89-362	378-21
68	530-00	89-362	-378-21	77	530-00	89-362	378-21
69	530-00	89-362	-378-21	78	530-00	89-362	378-21
70	530-00	89-362	-378-21	79	530-00	89-362	378-21
71	530-00	89-362	-378-21	80	530-00	89-362	378-21
72	530-00	89-362	-378-21	81	530-00	89-362	378-21
73	530-00	89-362	-378-21	82	530-00	89-362	378-21
74	530-00	89-362	-378-21	83	530-00	89-362	378-21
75	530-00	89-362	-378-21	84	530-00	89-362	378-21
76	530-00	89-362	-378-21	85	530-00	89-362	378-21
77	530-00	89-362	-378-21	86	530-00	89-362	378-21
78	530-00	89-362	-378-21	87	530-00	89-362	378-21
79	530-00	89-362	-378-21	88	530-00	89-362	378-21
80	530-00	89-362	-378-21	89	530-00	89-362	378-21
81	530-00	89-362	-378-21	90	530-00	89-362	378-21
82	530-00	89-362	-378-21	91	530-00	89-362	378-21
83	530-00	89-362	-378-21	92	530-00	89-362	378-21
84	530-00	89-362	-378-21	93	530-00	89-362	378-21
85	530-00	89-362	-378-21	94	530-00	89-362	378-21
86	530-00	89-362	-378-21	95	530-00	89-362	378-21
87	530-00	89-362	-378-21	96	530-00	89-362	378-21
88	530-00	89-362	-378-21	97	530-00	89-362	378-21
89	530-00	89-362	-378-21	98	530-00	89-362	378-21
90	530-00	89-362	-378-21	99	530-00	89-362	378-21
91	530-00	89-362	-378-21	100	530-00	89-362	378-21
92	530-00	89-362	-378-21	101	530-00	89-362	378-21
93	530-00	89-362	-378-21	102	530-00	89-362	378-21
94	530-00	89-362	-378-21	103	530-00	89-362	378-21
95	530-00	89-362	-378-21	104	530-00	89-362	378-21
96	530-00	89-362	-378-21	105	530-00	89-362	378-21
97	530-00	89-362	-378-21	106	530-00	89-362	378-21
98	530-00	89-362	-378-21	107	530-00	89-362	378-21
99	530-00	89-362	-378-21	108	530-00	89-362	378-21
100	530-00	89-362	-378-21	109	530-00	89-362	378-21
101	530-00	89-362	-378-21	110	530-00	89-362	378-21
102	530-00	89-362	-378-21	111	530-00	89-362	378-21
103	530-00	89-362	-378-21	112	530-00	89-362	378-21
104	530-00	89-362	-378-21	113	530-00	89-362	378-21
105	530-00	89-362	-378-21	114	530-00	89-362	378-21
106	530-00	89-362	-378-21	115	530-00	89-362	378-21
107	530-00	89-362	-378-21	116	530-00	89-362	378-21
108	530-00	89-362	-378-21	117	530-00	89-362	378-21
109	530-00	89-362	-378-21	118	530-00	89-362	378-21
110	530-00	89-362	-378-21	119	530-00	89-362	378-21
111	530-00	89-362	-378-21	120	530-00	89-362	378-21
112	530-00	89-362	-378-21	121	530-00	89-362	378-21
113	530-00	89-362	-378-21	122	530-00	89-362	378-21
114	530-00	89-362	-378-21	123	530-00	89-362	378-21
115	530-00	89-362	-378-21	124	530-00	89-362	378-21
116	530-00	89-362	-378-21	125	530-00	89-362	378-21
117	530-00	89-362	-378-21	126	530-00	89-362	378-21
118	530-00	89-362	-378-21	127	530-00	89-362	378-21
119	530-00	89-362	-378-21	128	530-00	89-362	378-21
120	530-00	89-362	-378-21	129	530-00	89-362	378-21
121	530-00	89-362	-378-21	130	530-00	89-362	378-21
122	530-00	89-362	-378-21	131	530-00	89-362	378-21
123	530-00	89-362	-378-21	132	530-00	89-362	378-21
124	530-00	89-362	-378-21	133	530-00	89-362	378-21
125	530-00	89-362	-378-21	134	530-00	89-362	378-21
126	530-00	89-362	-378-21	135	530-00	89-362	378-21
127	530-00	89-362	-378-21	136	530-00	89-362	378-21
128	530-00	89-362	-378-21	137	530-00	89-362	378-21
129	530-00	89-362	-378-21	138	530-00	89-362	378-21
130	530-00	89-362	-378-21	139	530-00	89-362	378-21
131	530-00	89-362	-378-21	140	530-00	89-362	378-21
132	530-00	89-362	-378-21	141	530-00	89-362	378-21
133	530-00	89-362					

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
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SAMPLE NO. 1

TIME	125	1	1.2461	1347.70	1947.00	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
STEP	ITER	OPTN	RAD (IN)	M WALL	M EDGE		
3	1	1	1.2461	1347.70	1947.00	.4743	.93775
B PRIME	B	PRIME	G	M DOT GAS	M DOT GAS	M CHAR (LB/SQ FT-SEC)	M GAS
.29705	.11900	.050584	.034214	.591677	.499702		
---ABLATION RATES---							
---RECESSIONS/RECESSION RATES---							
SURFACE (IN) / (IN/SEC)							
.0940590	.0085638	.1014950	.0084475	.3300085	.0177243	PYROLYSIS (.98)	
---SURFACE ENERGY FLUX TERMS---							
CURRENT RATES (BTU/SQ FT SURFACE-SEC)							
AND INTEGRATED VALUES (BTU/ORIO SQ FT)							
CONNECTED	IN	RADIATION	OUT	CHEMICAL	CONDUCTION		
RATE	.284+03	.870+03	.317+04	-.628+02	.474+03		
TOTAL	.437+04	.592+04	.385+04	-.286+03	.499+04		
---INTERIOR ENERGY TERMS---							
CURRENT RATES (BTU/SQ FT SURFACE-SEC)							
AND INTEGRATED VALUES (BTU/ORIO SQ FT)							
PYROL GAS	TEMP	DENSITY	ENTHALPY	TEMP	DENSITY	ENTHALPY	LOSS AT
PICK UP	(DEG R)	(LB/CU FT)	(BTU/LB)	(DEG R)	(LB/CU FT)	(BTU/LB)	HEAT FACE
RATE	.198+03	.233+02	.145+01	.184+03	.230+04	-.314+05	
TOTAL	.236+04	.432+03	.135+04	.236+04		-.824+04	
NODE MAT	TEMP	DENSITY	ENTHALPY	NODE MAT	TEMP	DENSITY	ENTHALPY
1	0	5044.67	71.003	2435.47	9	535.72	89.362
2	0	5059.10	71.017	2121.33	10	531.04	89.362
3	0	4378.80	71.124	1778.87	11	530.11	89.362
4	0	3416.50	71.382	1392.77	12	530.01	89.362
5	0	2351.63	74.640	845.95	13	530.00	89.362
6	0	1104.05	80.198	-171.50	14	530.00	89.362
7	1	665.50	89.362	-239.59	15	530.00	89.362
8	1	559.20	89.362	-369.89	16	530.00	89.362

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
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SAMPLE NO. 1

TIME	146	3	1	1.3250	1363.62	1947.00	HEAT COEFF (LB/SQ FT-SEC)	CH/CMO
STEP	ITER	OPTN	RAD (IN)	M WALL	M EDGE			
3	1	1	1.3250	1363.62	1947.00	.3595	.93513	
B PRIME	B	PRIME	G	M DOT	CHAR M DOT GAS	M CHAR (LB/ORG SQ FT)	M GAS	
.31252	.11892	.041901	.0257+8	.1113484	.811107			
---ABLATION RATES---								
---RECESSIONS/RECESSION RATES---								
SURFACE (IN) / (IN/SEC)								
.1749902/	.0070954	.3454744/	.0115171	.5032318/	.0128019	PYROLYSIS (.98)		
---SURFACE ENERGY FLUX TERMS---								
CURRENT RATES (BTU/SQ FT SURFACE-SEC)								
AND INTEGRATED VALUES (BTU/ONIO SQ FT)								
CONNECTED	IN	RADIATION	OUT	CHEMICAL	CONDUCTION			
RATE	.283+03	.570+03	.334+03	-.489+02	.369+03			
TOTAL	.701+04	.123+05	.678+04	-.108+04	.115+05			
---INTERIOR ENERGY TERMS---								
CURRENT RATES (BTU/SQ FT SURFACE-SEC)								
AND INTEGRATED VALUES (BTU/ONIO SQ FT)								
PYROL GAS	TEMP	DENSITY	ENTHALPY	TEMP	DENSITY	ENTHALPY	LOSS AT	
PICK UP	(DEG R)	(LB/CU FT)	(BTU/LB)	(DEG R)	(LB/CU FT)	(BTU/LB)	HEAT FACE	
RATE	.154+03	.244+04	.146+02	.184+03	.230+04	-.314+05		
TOTAL	.236+04	.432+03	.135+04	.230+04		-.324+04		
NODE MAT	TEMP	DENSITY	ENTHALPY	TEMP	DENSITY	ENTHALPY		
1	0	5761.03	70.980	2473.30	9	584.59	89.362	
2	0	5288.01	70.972	2237.02	10	546.05	89.362	
3	0	4792.04	70.982	1988.95	11	533.12	89.362	
4	0	4268.10	71.028	1726.24	12	530.47	89.362	
5	0	3535.86	71.245	1356.57	13	530.04	89.362	
6	0	2005.72	77.230	454.82	15	530.00	89.362	
7	0	1065.23	88.904	-198.22	16	530.00	89.362	
8	1	706.13	89.362	-328.01				

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

TIME	30.0000	SECONDS	M WALL	M EDGE	HEAT COEFF	CH/CMU
STEP	ITER	OPTN	RAD (IN)	(BTU/LB)	(BTU/50 FT-SEC)	(BTU/50 FT-SEC)
205	3	1	1.5370	1430.40	1947.00	.92413
---ABLATION RATES---						
M PRIME	B PRIME	G	M DOT	CHAM	M DOT	M GAS
			(LB/50 FT-SEC)	(LB/50 FT)	(LB/50 FT)	(LB/50 FT)
.37163	.15313		.024081	.016476	2.673523	1.006242
---RECESSIONS/RECESSION RATES---						
SURFACE	CHAM	(IN/SEC)	CHAM	(IN/SEC)	CHAM	(IN/SEC)
.38702267	.0040779		.72323657	.0071472	.94801117	.0103161
---SURFACE ENERGY FLUX TERMS---						
CURRENT RATES	(BTU/50 FT SURFACE-SEC)					
AND INTEGRATED VALUES	(BTU/50 FT)					
CONDUCTED	RADIATED	CHEMICAL	CONDUCTION			
IN	OUT	GENERATION	AWAY			
RATE	.935.02	.370.03	.340.01			
TOTAL	.137.05	.508.05	.241.04			
---INTERIOR ENERGY TERMS---						
CURRENT RATES	(BTU/50 FT SURFACE-SEC)					
AND INTEGRATED VALUES	(BTU/50 FT)					
PYROLYSIS	DECOMP	CONVECTION	STORAGE	LOSS AT		
PICK UP	ABSORPTION	WITH SOLID	IN SOLID	NEAR FACE		
RATE	.107.03	.899.01	.751.05	.531.02		
TOTAL	.106.05	.119.04	.776.04	.853.04		
MODE MAT	TEMP	DENSITY	ENTHALPY	MODE MAT	TEMP	DENSITY
(DEG R)	(BTU/LB)	(LB/50 FT)	(BTU/LB)	(DEG R)	(BTU/LB)	(LB/50 FT)
1	0	582.15	2429.33	8	1467.59	77.337
2	0	582.15	2429.33	9	1211.15	84.148
3	0	582.15	2429.33	10	555.49	89.362
4	0	4517.22	1852.45	11	555.49	89.362
5	0	4517.22	1852.45	12	555.49	89.362
6	0	3799.82	1493.77	13	533.62	486.000
7	0	2882.48	1030.14	14	532.65	486.000

TIME	30.0000	SECONDS	M WALL	M EDGE	HEAT COEFF	CH/CMU
STEP	ITER	OPTN	RAD (IN)	(BTU/LB)	(BTU/50 FT-SEC)	(BTU/50 FT-SEC)
104	3	1	1.1900	1399.80	1947.00	.92413
---ABLATION RATES---						
M PRIME	B PRIME	G	M DOT	CHAM	M DOT	M GAS
			(LB/50 FT-SEC)	(LB/50 FT)	(LB/50 FT)	(LB/50 FT)
.32419	.12328		.035027	.021473	1.567173	1.088958
---RECESSIONS/RECESSION RATES---						
SURFACE	CHAM	(IN/SEC)	CHAM	(IN/SEC)	CHAM	(IN/SEC)
.23098747	.0059314		.4525757	.0112430	.84361057	.0121794
---SURFACE ENERGY FLUX TERMS---						
CURRENT RATES	(BTU/50 FT SURFACE-SEC)					
AND INTEGRATED VALUES	(BTU/50 FT)					
CONDUCTED	RADIATED	CHEMICAL	CONDUCTION			
IN	OUT	GENERATION	AWAY			
RATE	.158.03	.570.03	.342.04	.323.03		
TOTAL	.911.04	.198.05	.107.04	.156.05		
---INTERIOR ENERGY TERMS---						
CURRENT RATES	(BTU/50 FT SURFACE-SEC)					
AND INTEGRATED VALUES	(BTU/50 FT)					
PYROLYSIS	DECOMP	CONVECTION	STORAGE	LOSS AT		
PICK UP	ABSORPTION	WITH SOLID	IN SOLID	NEAR FACE		
RATE	.113.04	.120.02	.184.03	.725.02		
TOTAL	.613.04	.769.03	.441.04	.424.04		
MODE MAT	TEMP	DENSITY	ENTHALPY	MODE MAT	TEMP	DENSITY
(DEG R)	(BTU/LB)	(LB/50 FT)	(BTU/LB)	(DEG R)	(BTU/LB)	(LB/50 FT)
1	0	576.50	2498.89	9	1467.59	77.337
2	0	576.50	2498.89	10	1211.15	84.148
3	0	498.16	2873.23	11	555.49	89.362
4	0	498.16	2873.23	12	555.49	89.362
5	0	498.16	2873.23	13	555.49	89.362
6	0	3799.82	1493.77	14	533.62	486.000
7	0	2882.48	1030.14	15	532.65	486.000
8	0	236.50	89.292	16	250.76	

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
PAGE 25
SAMPLE NO. 1

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TIME SURF PROB SURFACE M WALL M EDGE M CHAK M GAS
STEP ITER OPTN RAD (IN) (BTU/LB) (BTU/LB) (LB/SQ FT-SEC) CH/CHO
245 3 1.5371 3125.63 .00 .0000 .0000 .0000 .0000

M PRIME B PRIME G M DOT CHAM M DOT GAS M CHAK M GAS
.00000 .00000 .013143 2.673845 1.911224

---ABLATION RATES---
(LB/SQ FT-SEC)
.000000 .000000 .000000 .000000 .000000 .000000

---NECESSATIONS/RECUSSION RATES---
(IN) CHAM (IN/SEC) PYROLYSIS (.98)
.3870633/ .00000000 .7646316/ .0039014 .9943477/ .0080042

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SURFACE SURFACE SURFACE SURFACE SURFACE SURFACE SURFACE SURFACE
.3870633/ .00000000 .7646316/ .0039014 .9943477/ .0080042

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/CHIO SQ FT)
CONDUCTED IN OUT RADIATED IN OUT CHEMICAL GENERATION CONDUCTION AWAY
RATE .000 .000 .000 .000 .000 .000 .000 .000 .000 .000 .000 .000
TOTAL .13705 .13705 .13705 .13705 .13705 .13705 .13705 .13705 .13705 .13705 .13705 .13705

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PYROL GAS PICK UP ABSORPTION WITH SOLID IN SOLID STORAGE LOSS AT REAR FACE
RATE .54302 .03601 .000 .000 .000 .000 .000 .000 .000 .000 .000 .000
TOTAL .11105 .12404 .077604 .59104 .000 .000 .000 .000 .000 .000 .000 .000

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N OE MAT TEMP DENSITY ENTHALPY NODE MAT TEMP DENSITY ENTHALPY
(DEC R) (LB/CO FT) (BTU/LB) (DEC R) (LB/CO FT) (BTU/LB)
1 0 2085.65 71.148 1086.67 16 7 534.31 486.000 .00
2 0 4174.25 70.911 1665.73 8 7 218.41 520.69
3 0 4014.87 70.910 1602.45 10 7 200.52 486.000 .00
4 0 3878.55 70.933 1536.89 12 7 574.91 486.000 .00
5 0 3561.22 70.977 1376.46 15 7 534.31 486.000 .00
6 0 2085.65 71.148 1086.67 16 7 534.31 486.000 .00

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AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
PAGE 30
SAMPLE NO. 1

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TIME SURF PROB SURFACE M WALL M EDGE M CHAK M GAS
STEP ITER OPTN RAD (IN) (BTU/LB) (BTU/LB) (LB/SQ FT-SEC) CH/CHO
203 3 1.5371 527.74 .00 .0000 .0000 .0000 .0000

M PRIME B PRIME G M DOT CHAM M DOT GAS M CHAK M GAS
.00000 .00000 .000000 .000000 .000000 .000000 .000000 .000000 .000000 .000000

---ABLATION RATES---
(LB/SQ FT-SEC)
.000000 .000000 .000000 .000000 .000000 .000000

---NECESSATIONS/RECUSSION RATES---
(IN) CHAM (IN/SEC) PYROLYSIS (.98)
.3870633/ .00000000 .8166857/ .0006198 1.1258767/ .0031283

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SURFACE SURFACE SURFACE SURFACE SURFACE SURFACE SURFACE SURFACE
.3870633/ .00000000 .8166857/ .0006198 1.1258767/ .0031283

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/CHIO SQ FT)
CONDUCTED IN OUT RADIATED IN OUT CHEMICAL GENERATION CONDUCTION AWAY
RATE .000 .000 .000 .000 .000 .000 .000 .000 .000 .000 .000 .000
TOTAL .13705 .13705 .13705 .13705 .13705 .13705 .13705 .13705 .13705 .13705 .13705 .13705

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PYROL GAS PICK UP ABSORPTION WITH SOLID IN SOLID STORAGE LOSS AT REAR FACE
RATE .85301 .15301 .000 .000 .000 .000 .000 .000 .000 .000 .000 .000
TOTAL .11905 .13504 .077604 .48804 .000 .000 .000 .000 .000 .000 .000 .000

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N OE MAT TEMP DENSITY ENTHALPY NODE MAT TEMP DENSITY ENTHALPY
(DEC R) (LB/CO FT) (BTU/LB) (DEC R) (LB/CO FT) (BTU/LB)
1 0 2085.65 71.148 1086.67 16 7 534.31 486.000 .00
2 0 4174.25 70.911 1665.73 8 7 218.41 520.69
3 0 4014.87 70.910 1602.45 10 7 200.52 486.000 .00
4 0 3878.55 70.933 1536.89 12 7 574.91 486.000 .00
5 0 3561.22 70.977 1376.46 15 7 534.31 486.000 .00
6 0 2085.65 71.148 1086.67 16 7 534.31 486.000 .00

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TIME	SURF	PROB	SURFACE	M WALL	M EDGE	HEAT COEFF	CM/CHD
STEP	ITEM	OPTN	RAD (IN)	(BTU/LB)	(BTU/LB)	(LB/50 FT-SEC)	
319	3	3	1.5371	-185.91	.00	.0000	.00000
---ABLATION RATES---							
B PRIME	B PRIME	G	M DOT CHAM	M DOT GAS	M CHAM	M GAS	
			(LB/50 FT-SEC)	(LB/50 FT-SEC)	(LB/50 FT-SEC)	(LB/50 FT-SEC)	
.00000	.00000	.00000	.000000	.002150	2.67365	2.30115	
---RECESSIONS/RECESSION RATES---							
SURFACE			CHAM	(IN/SEC)	PYROLYSIS (IN/SEC)		
.38706137			.0000000	.0000000	.0000000		
---SURFACE ENERGY FLUX TERMS---							
CURRENT RATES (BTU/50 FT SURFACE-SEC)							
AND INTEGRATED VALUES (BTU/50 FT)							
CONVECTED IN							
RADIATED OUT							
CHEMICAL GENERATION							
CONDUCTION AWAY							
RATE	.000	.000	.000	.000	.000	.000	.000
TOTAL	.137+05	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---							
CURRENT RATES (BTU/50 FT SURFACE-SEC)							
AND INTEGRATED VALUES (BTU/50 FT)							
PYROLYSIS							
CONVECTION							
STORAGE							
LOSS AT							
NEAR FACE							
RATE	.252+01	.510+00	.000	.000	.000	.000	.000
TOTAL	.121+05	.138+04	.000	.000	.000	.000	.000

TIME	SURF	PROB	SURFACE	M WALL	M EDGE	HEAT COEFF	CM/CHD
STEP	ITEM	OPTN	RAD (IN)	(BTU/LB)	(BTU/LB)	(LB/50 FT-SEC)	
307	3	3	1.5371	-45.46	.00	.0000	.00000
---ABLATION RATES---							
B PRIME	B PRIME	G	M DOT	CHAM	M DOT	GAS	M GAS
			(LB/50 FT-SEC)	(LB/50 FT-SEC)	(LB/50 FT-SEC)	(LB/50 FT-SEC)	(LB/50 FT-SEC)
.00000	.00000	.00000	.00000	.002150	2.67365	2.30115	2.260376
---RECESSIONS/RECESSION RATES---							
SURFACE			CHAM	(IN/SEC)	PYROLYSIS (IN/SEC)		
.38706137			.0000000	.0000000	.0000000		
---SURFACE ENERGY FLUX TERMS---							
CURRENT RATES (BTU/50 FT SURFACE-SEC)							
AND INTEGRATED VALUES (BTU/50 FT)							
CONVECTED IN							
RADIATED OUT							
CHEMICAL GENERATION							
CONDUCTION AWAY							
RATE	.000	.000	.000	.000	.000	.000	.000
TOTAL	.137+05	.000	.000	.000	.000	.000	.000
---INTERIOR ENERGY TERMS---							
CURRENT RATES (BTU/50 FT SURFACE-SEC)							
AND INTEGRATED VALUES (BTU/50 FT)							
PYROLYSIS							
CONVECTION							
STORAGE							
LOSS AT							
NEAR FACE							
RATE	.252+01	.510+00	.000	.000	.000	.000	.000
TOTAL	.121+05	.138+04	.000	.000	.000	.000	.000

OUTPUT, SAMPLE PROBLEM 1 (CONCLUDED)

CMA/CRM ANALYSIS AT ABLATIVE THROAT OF A SOLID PROPELLANT ROCKET MOTOR
 THROAT SURFACE IS CARBON PHENOLIC AT A 60 DEGREE LAYUP ANGLE, P=29 ATM
 SILICA PHENOLIC DECOMPOSING BACK-UP MATL WITH F-FUNCTIONS SAMPLE NO. 2

A	20.25	0.0	1.400+04	3.00	1.540+04	1000.0	
B	60.75	32.40	4.480+09	3.00	3.680+04	600.0	
C	94.50	94.50	0.0	0.0	0.0	90000.0	1
	191 3 2	0.0	120.0	0.5	2.0	5.0	1.0 0.3750
	7.0	10.0	0.04	-376.5	0.0	0.0	-0.345 536.
	1.0	1.08	1.4				
531.	1000.						
A	20.250	0.0	0.140+05	3.0	0.154+05	1000.	
B	60.750	40.50	0.448+10	3.0	0.368+05	600.0	
C	129.00	129.0	0.0	0.0	0.0	90000.	
			-4807.0	-5280.0	0.0	-0.315	536.0
1	530.0	0.020	1.15				
1	530.0	0.040					
1	530.0	0.040					
1	530.0	0.040					
1	530.0	0.060					
1	530.0	0.100					
1	530.0	0.100					
1	530.0	0.100					
1	530.0	0.150					
1	530.0	0.150					
22	530.0	0.020					
22	530.0	0.040					
22	530.0	0.040					
22	530.0	0.100					
22	530.0	0.100					
22	530.0	0.100					
22	530.0	0.100					
22	530.0	0.250					
3	530.0	0.250					
3	530.0	0.250					
	0.0	0.0	530.0				1
	530.0	0.210	1.880-04	0.630	MX4926 (VIRGIN.60 DEG LAYUP)		
	800.0	0.360	2.130-04	0.630	MX4926 (VIRGIN.60 DEG LAYUP)		
	1160.0	0.360	2.470-04	0.630	MX4926 (VIRGIN.60 DEG LAYUP)		
	1500.0	0.472	2.470-04	0.630	MX4926 (VIRGIN.60 DEG LAYUP)		
	2000.0	0.484	2.470-04	0.630	MX4926 (VIRGIN.60 DEG LAYUP)		
	3000.0	0.493	2.470-04	0.630	MX4926 (VIRGIN.60 DEG LAYUP)		
	4000.0	0.498	2.470-04	0.630	MX4926 (VIRGIN.60 DEG LAYUP)		
	5000.0	0.500	2.470-04	0.630	MX4926 (VIRGIN.60 DEG LAYUP)		
-1	6000.0	0.500	2.470-04	0.630	MX4926 (VIRGIN.60 DEG LAYUP)		
	530.0	0.210	2.470-04	0.630	MX4926 (CHAR. 60 DEG LAYUP)		
	1000.0	0.430	2.530-04	0.630	MX4926 (CHAR. 60 DEG LAYUP)		
	1500.0	0.472	2.580-04	0.630	MX4926 (CHAR. 60 DEG LAYUP)		
	2000.0	0.484	3.240-04	0.630	MX4926 (CHAR. 60 DEG LAYUP)		
	3000.0	0.493	7.190-04	0.630	MX4926 (CHAR. 60 DEG LAYUP)		
	4000.0	0.498	1.340-03	0.630	MX4926 (CHAR. 60 DEG LAYUP)		
	5000.0	0.500	2.800-03	0.630	MX4926 (CHAR. 60 DEG LAYUP)		
-1	6000.0	0.500	2.750-03	0.630	MX4926 (CHAR. 60 DEG LAYUP)		
	530.0	0.260	0.0001070				
	800.0	0.275	0.000109				
	1160.0	0.310	0.000110				
	1500.0	0.472	0.000110				
	2000.0	0.484	0.000110				
	3000.0	0.493	0.000110				
	4000.0	0.493	0.000110				
-1	5000.0	0.500	0.0001100				
	530.0	0.210	0.000310				
	1000.0	0.430	0.000330				
	1500.0	0.472	0.000335				
	2000.0	0.484	0.000354				
	3000.0	0.493	0.000383				
	3500.0	0.495	0.000395				
	4000.0	0.498	0.000427				
-1	5000.0	0.500	0.000502				
3	400.00						
	500.0	0.110	0.000694				
-1	5000.0	0.110	0.000694				
4	0.0						
	0.0	0.0	1.0				
-1	1.0	1.0	0.0				
5	0.001						
	0.0	0.0	1.0				
	0.35	0.4	1.0				
	0.600	0.4	0.0				
	0.90	0.4	0.0				
-1	1.00	1.0	0.0				
	900.0	1800.0	2700.0	3600.0	4500.0	5400.0	6300.0
	-1782.0	-930.2	195.6	2289.0	3600.0	4696.0	6152.0
	0.0	1947.0	904.0	0.8588	29.2		
	10.0	1947.0	904.0	0.7238	29.2		
	60.000	1947.0	904.0	0.7238	29.2		
	60.000	.05	0.				
1	120.	.05	0.				
	0.607	1.0	0.625				
	29.20		3500.0	0.0	914.106	914.106-1	
	29.20		3000.0	0.0	671.985	671.985-1	
	29.20		2500.0	0.0	434.119	434.119-1	
	29.20		2000.0	0.0	202.668	202.668-1	
	29.20		1500.0	0.0	-20.763	-20.763-1	
	29.20		1000.0	0.0	-231.356	-231.356-1	
	29.20		500.0	0.0	-405.022	-405.022-1	
29.20000	0.50000	0.35000	30.72130.	2054.193	2054.193	1	C0 0.
29.20000	0.50000	0.20000	3299.77410.	1697.988	1697.988	1	C0 0.

INPUT, SAMPLE PROBLEM 2

24.20000	0.50000	0.15000	1239.26709	1557.984	1557.984	1	C*	0.
24.20000	0.50000	0.10000	1165.21060	1403.100	1403.100	1	C*	0.
24.20000	0.50000	0.05000	1063.66700	1224.521	1224.521	1	C*	0.
24.20000	0.50000	0.10010	2914.24580	1025.664	1025.664	1	C*	0.
24.20000	0.50000	0.00010	2500.00000	645.109	645.109	0	C*	0.
24.20000	0.50000	0.00010	2000.00000	294.892	294.892	0	C*	0.
24.20000	0.50000	0.00010	1500.00000	-250.818	-250.818	0	AL203*	0.
24.20000	0.50000	0.00010	1000.00000	-412.740	-412.740	0	AL203*	0.
24.20000	0.50000	0.00010	500.00000	-1305.336	-1305.336	0	AL203*	0.
24.20000	0.20000	0.15000	1419.01650	1814.074	1814.074	1	C*	0.
24.20000	0.20000	0.20000	1243.10580	1142.244	1142.244	1	C*	0.
24.20000	0.20000	0.15000	1136.66150	1142.244	1142.244	1	C*	0.
24.20000	0.20000	0.10000	2981.30240	907.434	907.434	1	C*	0.
24.20000	0.20000	0.05000	2714.33540	602.753	602.753	1	C*	0.
24.20000	0.20000	0.01000	2525.79420	435.126	435.126	1	C*	0.
24.20000	0.20000	0.01000	2116.21660	145.414	145.414	1	C*	0.
24.20000	0.20000	0.00750	1952.70850	42.720	42.720	1	C*	0.
24.20000	0.20000	0.00500	1244.38790	-494.248	-494.248	1	C*	0.
24.20000	0.20000	0.00101	252.80290	-552.718	-552.718	1	C*	0.
24.20000	0.20000	0.00010	1000.00000	-1012.490	-1012.490	0	AL203*	0.
24.20000	0.20000	0.00010	500.00000	-1353.107	-1353.107	0	AL203*	0.
24.20000	0.10000	0.15000	1443.87980	1718.127	1718.127	1	C*	0.
24.20000	0.10000	0.20000	1209.53360	1182.973	1182.973	1	C*	0.
24.20000	0.10000	0.15000	1067.38430	949.646	949.646	1	C*	0.
24.20000	0.10000	0.10000	2710.58750	656.888	656.888	1	C*	0.
24.20000	0.10000	0.05000	2170.43020	138.870	138.870	1	C*	0.
24.20000	0.10000	0.04000	1272.99140	-528.689	-528.689	1	C*	0.
24.20000	0.10000	0.01000	101214.70430	-629.431	-629.431	1	C*	0.
24.20000	0.10000	0.01000	101011.71570	-799.809	-799.809	1	C*	0.
24.20000	0.10000	0.00010	10095.31170	-884.688	-884.688	1	C*	0.
24.20000	0.10000	0.00010	10000.00000	-1045.958	-1045.958	0	AL203*	0.
24.20000	0.10000	0.00010	500.00000	-1374.827	-1374.827	0	AL203*	0.
24.20000	0.06000	0.15000	1446.24560	1674.103	1674.103	1	C*	0.
24.20000	0.06000	0.20000	1191.95550	1111.021	1111.021	1	C*	0.
24.20000	0.06000	0.15000	1024.23220	859.936	859.936	1	C*	0.
24.20000	0.06000	0.10000	2731.50620	531.322	531.322	1	C*	0.
24.20000	0.06000	0.08000	2506.35480	344.891	344.891	1	C*	0.
24.20000	0.06000	0.07000	2314.56540	211.524	211.524	1	C*	0.
24.20000	0.06000	0.06500	2151.65580	109.606	109.606	1	C*	0.
24.20000	0.06000	0.06000	1325.71120	-461.918	-461.918	1	C*	0.
24.20000	0.06000	0.05000	1241.34440	-583.801	-583.801	1	C*	0.
24.20000	0.06000	0.03000	1151.88170	-758.859	-758.859	1	C*	0.
24.20000	0.06000	0.00010	101018.34140	-1033.389	-1033.389	1	C*	0.
24.20000	0.06000	0.00010	10000.00000	-1061.054	-1061.054	0	AL203*	0.
24.20000	0.06000	0.00010	500.00000	-1384.661	-1384.661	0	AL203*	0.
24.20000	0.03500	0.15000	1448.08240	1645.678	1645.678	1	C*	0.
24.20000	0.03500	0.20000	1179.22710	1063.164	1063.164	1	C*	0.
24.20000	0.03500	0.15000	2998.60670	799.242	799.242	1	C*	0.
24.20000	0.03500	0.10000	2645.98070	440.337	440.337	1	C*	0.
24.20000	0.03500	0.08000	2376.98750	206.774	206.774	1	C*	0.
24.20000	0.03500	0.07500	2166.44010	106.992	106.992	1	C*	0.
24.20000	0.03500	0.07000	137.17750	-452.619	-452.619	1	C*	0.
24.20000	0.03500	0.06000	1245.53300	-578.870	-578.870	1	C*	0.
24.20000	0.03500	0.05000	1134.91430	-670.371	-670.371	1	C*	0.
24.20000	0.03500	0.00010	499.26150	-1195.571	-1195.571	1	C*	0.
24.20000	0.03500	0.00010	500.00000	-1391.193	-1391.193	0	C*	0.
24.20000	0.02000	0.15000	1449.20720	1624.023	1624.023	1	C*	0.
24.20000	0.02000	0.20000	1170.86300	1033.320	1033.320	1	C*	0.
24.20000	0.02000	0.15000	2978.39280	760.809	760.809	1	C*	0.
24.20000	0.02000	0.10000	2582.78380	378.825	378.825	1	C*	0.
24.20000	0.02000	0.08000	2179.85570	78.164	78.164	1	C*	0.
24.20000	0.02000	0.07500	1328.44640	-469.197	-469.197	1	C*	0.
24.20000	0.02000	0.07000	1275.99870	-533.272	-533.272	1	C*	0.
24.20000	0.02000	0.06000	1215.23460	-632.586	-632.586	1	C*	0.
24.20000	0.02000	0.05000	1170.94980	-718.468	-718.468	1	C*	0.
24.20000	0.02000	0.00010	685.98190	-1350.252	-1350.252	1	C*	0.
24.20000	0.02000	0.00010	500.00000	-1395.265	-1395.265	0	AL203*	0.
24.20000	0.00010	0.15000	1450.80590	1604.023	1604.023	1	C*	0.
24.20000	0.00010	0.20000	1158.75570	992.289	992.289	1	C*	0.
24.20000	0.00010	0.15000	2944.10120	787.221	787.221	1	C*	0.
24.20000	0.00010	0.10000	2472.02610	284.658	284.658	1	C*	0.
24.20000	0.00010	0.02500	2306.33350	175.096	175.096	1	C*	0.
24.20000	0.00010	0.01500	2119.58270	62.729	62.729	1	C*	0.
24.20000	0.00010	0.00500	1914.41820	-56.221	-56.221	1	C*	0.
24.20000	0.00010	0.00250	1330.25040	-466.518	-466.518	1	C*	0.
24.20000	0.00010	0.00001	299.59080	-503.670	-503.670	1	C*	0.
24.20000	0.00010	0.00001	1181.20300	-698.006	-698.006	1	C*	0.
24.20000	0.00010	0.00001	1140.40500	-780.959	-780.959	1	C*	0.
24.20000	0.00010	0.00010	600.47750	-1384.243	-1384.243	1	C*	0.
24.20000	0.00010	0.00010	500.00000	-1400.855	-1400.855	0	AL203*	0.

INPUT, SAMPLE PROBLEM 2 (CONCLUDED)

CHM/COM ANALYSIS AT RELATIVE INITIAL OF A SOLID PROPELLANT ROCKET MOTOR THROUGH SURFACE IS CARBON PRENUCLIC AT A 90 DEGREE LATUM ANGLE. P29 ATM SILICA PRENUCLIC DECOMPOSING BACK-UP ATL WITH F-FUNCTIONS SAMPLE NO. 2

---REACTION KINETIC EQUATION---

UNNU/UTIME = GAMMA (DGEAP(-LH/1)MHUA((MHGA-MHOMAI)/MHODAI+PPSIA)
+ GAMMA (DGEAP(-LH/1)MHOD((MHOB-MHOMBI)/MHODBI+PPSIB)
+ (1-GAMMA) (DGEAP(-LH/1)MHOC((MHOC-MHOMC)/MHODC+PPSIC)

---REACTION KINETIC CONSTANTS---

REACTION RHOD " PSI E T REAC
(LB/FT) (1/SEC) (DEG R) (DEG R)
A 20.25 .06 .1400+05 3.00 .1540+05 1000.
B 60.75 32.48 .4400+13 3.00 .3480+85 688.
C 94.50 74.50 .0000+00 3.00 .0000 94000.
RESIN VOLUME FRACTION: GAMMA = .231 MASS FRACTION: .3451

---DECOMPOSING BACK-UP KINETICS---

REACTION RHOD RHOR PSI E T REAC
(LB/FT) (1/SEC) (DEG R) (DEG R)
A 20.25 .00 .1400+05 3.00 .1540+05 1000.
B 60.75 48.50 .4400+13 3.00 .3480+85 688.
C 129.00 129.00 .0000+00 3.00 .0000 94000.
RESIN VOLUME FRACTION: GAMMA = .231 MASS FRACTION: .3151

---TIME INCREMENT INFORMATION---

INITIAL TIME (SEC) .000 FINAL TIME (SEC) 120.00
OUTPUT INTERVAL = .500 SEC FROM INITIAL TIME UNTIL 2.000 SEC
OUTPUT INTERVAL = 2.000 SEC FROM 2.000 SEC UNTIL 10.000 SEC
OUTPUT INTERVAL = 5.000 SEC FROM 10.000 SEC UNTIL FINAL TIME
MAXIMUM TIME STEP = 1.00 SECONDS

---MOUL DATA---

NO. 1	NO. 2	NO. 3	NO. 4	NO. 5	NO. 6	NO. 7	NO. 8	NO. 9	NO. 10	NO. 11	NO. 12	NO. 13	NO. 14	NO. 15	NO. 16	NO. 17	NO. 18	NO. 19
1	1	1	1	1	1	1	1	1	1	1	22	22	22	22	22	22	22	3
TEMPERATURE (DEG. HANKINE)	530.00	530.00	530.00	530.00	530.00	530.00	530.00	530.00	530.00	530.00	530.00	530.00	530.00	530.00	530.00	530.00	530.00	530.00
RELATIVE AREA	.2150+01	.1190+01	.1230+01	.1270+01	.1320+01	.1400+01	.1500+01	.1600+01	.1745+01	.1980+01	.2030+01	.2200+01	.2500+01	.2500+01	.2500+01	.2500+01	.2500+01	.2500+01
THICKNESS (INCHES)	.02000	.04000	.04000	.04000	.04000	.04000	.04000	.04000	.04000	.04000	.04000	.04000	.04000	.04000	.04000	.04000	.04000	.04000
MOUL DEPTH (INCHES)	.000000	.040000	.090000	.120000	.170000	.250000	.350000	.450000	.575000	.810000	.880000	.950000	1.050000	1.150000	1.300000	1.525000	1.775000	1.775000
CONT. RESISTANCE (SOFT-S-DEG/FTU)	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000

INITIAL INGRESSIVE RATE OF LAST ABLATION MOUL (INCHES) .0400
MINIMUM THICKNESS OF LAST ABLATION MOUL (INCHES) .0400
THERE ARE 10 MODELETS ASSIGNED TO EACH ABLATING MOUL

---HEAT OF FORMATION OF MATERIAL CONSTITUENTS---
PLASTIC CHM -376.50 GAS .00
ENTHALPY DATUM TEMPERATURE = 530.000 DEG HANKINE
COEF BTU/FTSQ-SEC-DEG R BACK WALL EMISSIVITY .000
COEF BTU/FTSQ-SEC-DEG R BACK WALL TEMPERATURE 530.00
---DECOMPOSING BACK-UP NO. 1
PLASTIC CHM -5280.00 GAS .00
ENTHALPY DATUM TEMPERATURE = 530.000 DEG HANKINE

---MATERIAL THERMAL PROPERTY DATA---
MATERIAL NO. 1 MATERIAL NO. 2 MATERIAL NOS. 3 THROUGH 10
VIRGIN PLASTIC CHM
DECOMPOSING BACK-UP VIRGIN MATERIALS 23.15+05.00, CHM MATERIALS 23.25+07.00

ALCOTHEM CHARGING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM

PAGE 3
SAMPLE NO. 2

MATERIAL NO. 1 TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	DENSITY = 89.362 LB/CU FT	SENSIBLE ENTHALPY (BTU/LB)	EMISSION
530.00	.2100	.0001800	-1.71	.6300	
800.00	.3600	.0002130	75.24	.6300	
1150.00	.3600	.0002470	204.84	.6300	
1500.00	.4720	.0002470	346.28	.6300	
2000.00	.4840	.0002470	585.28	.6300	
3000.00	.4950	.0002470	1073.78	.6300	
4000.00	.4980	.0002470	1569.28	.6300	
5000.00	.5000	.0002470	2084.28	.6300	
6000.00	.5000	.0002470	2568.28	.6300	

MATERIAL NO. 2 TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	DENSITY = 70.484 LB/CU FT	SENSIBLE ENTHALPY (BTU/LB)	EMISSION
530.00	.2100	.0002470	-1.71	.6300	
800.00	.3600	.0002530	144.48	.6300	
1500.00	.4720	.0002540	373.98	.6300	
2000.00	.4840	.0002640	612.98	.6300	
3000.00	.4930	.0002790	1101.48	.6300	
4000.00	.4980	.0002800	1598.98	.6300	
5000.00	.5000	.0002800	2095.98	.6300	
6000.00	.5000	.0002750	2585.98	.6300	

MATERIAL NO. 22 TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	DENSITY = 188.708 LB/CU FT	SENSIBLE ENTHALPY (BTU/LB)	EMISSION
530.00	.2800	.0001070	-1.43		
800.00	.2750	.0001090	78.62		
1100.00	.3100	.0001100	175.92		
1500.00	.4720	.0001108	308.86		
2000.00	.4840	.0001180	547.86		
3000.00	.4930	.0001180	1038.36		
4000.00	.4980	.0001108	1528.36		
5000.00	.5000	.0001108	2025.86		

ALCOTHEM CHARGING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM

PAGE 4
SAMPLE NO. 2

MATERIAL NO. 3 TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	DENSITY = 88.000 LB/CU FT	SENSIBLE ENTHALPY (BTU/LB)	EMISSION
500.00	.1100	.0009400			
5000.00	.1100	.0009400			

TABLES OF OPTIONAL MASS-FUNCTION FUNCTIONS FOR THERMAL CONDUCTIVITY

$K = F1(X) * F2(X) * F3(X)$

F-FUNCTION TABLE NO. 1 ASSIGNED TO MAIN MATERIAL

X	F1(X)	F2(X)	F3(X)
.0000	.0000	.0000	.0000
1.0000	.0000	.0000	.0000

F-FUNCTION TABLE NO. 2 ASSIGNED TO DECOMPOSING MATERIAL NO. 1

X	F1(X)	F2(X)	F3(X)
.0000	.0000	.0000	.0000
.5000	.0000	.0000	.0000
.9800	.0000	.0000	.0000
1.0000	.0000	.0000	.0000

---RESIN DECOMPOSITION GAS SENSIBLE ENTHALPY---

TEMPERATURE (DEG R)	900.00	1800.00	2700.00	3600.00	4500.00
ENTHALPY (BTU/LB)	-1782.00	-930.20	195.60	2289.00	3600.00

TEMPERATURE (DEG R)	5400.00	6300.00
ENTHALPY (BTU/LB)	4698.00	6152.00

---TIME DEPENDENT BOUNDARY CONDITIONS---

TIME (SEC)	PROB OPTN	CH/CHO	SENSIBLE ENTHALPY (BTU/LB)	RADIATION HEAT RATE (BTU/30 FT-SECOND)	HEAT COEFF (LB/30 FT-SECOND)	PRESSURE (ATM)	FLOWING REDUCTION PARAMETER
.00	1	1	194.00	904.00	.0588	29.20000	.332
10.00	1	1	194.00	904.00	.0588	29.20000	.372
60.00	1	1	194.00	904.00	.0588	29.20000	.375
120.00	3	3	.05	.05	.00	.00	

CH/CHO = PH1/(EXP(PH1)-1.) WHERE PH1 = 2.08KPM DOT/CHO. SHP IN TABLE

OUTPUT, SAMPLE PROBLEM 2 (CONTINUED)

---SURFACE EQUILIBRIUM DATA---
RATIO OF MASS TO HEAT TRANSFER COEFFICIENTS = .002
UNEQUAL DIFFUSION EXPONENT = .000
NOMINAL SURFACE VIEW FACTOR = 1.000 (OPTION 1)
FISSENG MODEL NOT USED FOR GAS TERMS BY (M INITIAL/R CURRENT) * 0.001
HEAT TRANSFER COEFFICIENT MULTIPLIED BY (M INITIAL/R CURRENT) * 0.001
WHERE T = (1.8 * 273.15) + (T - 32) * 5/9
IN THIS MODEL, THE BURNING RATE EXPONENT
IN THIS MODEL, THE BURNING RATE EXPONENT
NO. CHAR-SHELL CONNECTION ON SURFACE REACTION

P = 29.2000 ATM
TEMPERATURE EDGE ENTH TEMPERATURE EDGE ENTH
(DEG R) AT I-WALL (DEG R) AT I-WALL
6300.00 1445.39 3000.00 344.00
5400.00 1200.57 2700.00 -37.37
4300.00 781.61 1800.00 -616.44

M-DOT-CHAR/CM M-DOT-CHAR/CM M-DOT-CHAR/CM
TEMP (DEG R) M-DOT-CHAR/CM TEMP (DEG R) M-DOT-CHAR/CM TEMP (DEG R) M-DOT-CHAR/CM
1000.00 -0.001 1000.00 -0.001 1000.00 -0.001
1500.00 -0.001 1500.00 -0.001 1500.00 -0.001
2000.00 -0.001 2000.00 -0.001 2000.00 -0.001
2500.00 -0.001 2500.00 -0.001 2500.00 -0.001
3000.00 -0.001 3000.00 -0.001 3000.00 -0.001
3500.00 -0.001 3500.00 -0.001 3500.00 -0.001
4000.00 -0.001 4000.00 -0.001 4000.00 -0.001
4500.00 -0.001 4500.00 -0.001 4500.00 -0.001
5000.00 -0.001 5000.00 -0.001 5000.00 -0.001
5500.00 -0.001 5500.00 -0.001 5500.00 -0.001
6000.00 -0.001 6000.00 -0.001 6000.00 -0.001
6500.00 -0.001 6500.00 -0.001 6500.00 -0.001
7000.00 -0.001 7000.00 -0.001 7000.00 -0.001
7500.00 -0.001 7500.00 -0.001 7500.00 -0.001
8000.00 -0.001 8000.00 -0.001 8000.00 -0.001
8500.00 -0.001 8500.00 -0.001 8500.00 -0.001
9000.00 -0.001 9000.00 -0.001 9000.00 -0.001
9500.00 -0.001 9500.00 -0.001 9500.00 -0.001
10000.00 -0.001 10000.00 -0.001 10000.00 -0.001

M-DOT-CHAR/CM M-DOT-CHAR/CM M-DOT-CHAR/CM
TEMP (DEG R) M-DOT-CHAR/CM TEMP (DEG R) M-DOT-CHAR/CM TEMP (DEG R) M-DOT-CHAR/CM
1000.00 -0.001 1000.00 -0.001 1000.00 -0.001
1500.00 -0.001 1500.00 -0.001 1500.00 -0.001
2000.00 -0.001 2000.00 -0.001 2000.00 -0.001
2500.00 -0.001 2500.00 -0.001 2500.00 -0.001
3000.00 -0.001 3000.00 -0.001 3000.00 -0.001
3500.00 -0.001 3500.00 -0.001 3500.00 -0.001
4000.00 -0.001 4000.00 -0.001 4000.00 -0.001
4500.00 -0.001 4500.00 -0.001 4500.00 -0.001
5000.00 -0.001 5000.00 -0.001 5000.00 -0.001
5500.00 -0.001 5500.00 -0.001 5500.00 -0.001
6000.00 -0.001 6000.00 -0.001 6000.00 -0.001
6500.00 -0.001 6500.00 -0.001 6500.00 -0.001
7000.00 -0.001 7000.00 -0.001 7000.00 -0.001
7500.00 -0.001 7500.00 -0.001 7500.00 -0.001
8000.00 -0.001 8000.00 -0.001 8000.00 -0.001
8500.00 -0.001 8500.00 -0.001 8500.00 -0.001
9000.00 -0.001 9000.00 -0.001 9000.00 -0.001
9500.00 -0.001 9500.00 -0.001 9500.00 -0.001
10000.00 -0.001 10000.00 -0.001 10000.00 -0.001

---SURFACE EQUILIBRIUM DATA---
RATIO OF MASS TO HEAT TRANSFER COEFFICIENTS = .002
UNEQUAL DIFFUSION EXPONENT = .000
NOMINAL SURFACE VIEW FACTOR = 1.000 (OPTION 1)
FISSENG MODEL NOT USED FOR GAS TERMS BY (M INITIAL/R CURRENT) * 0.001
HEAT TRANSFER COEFFICIENT MULTIPLIED BY (M INITIAL/R CURRENT) * 0.001
WHERE T = (1.8 * 273.15) + (T - 32) * 5/9
IN THIS MODEL, THE BURNING RATE EXPONENT
IN THIS MODEL, THE BURNING RATE EXPONENT
NO. CHAR-SHELL CONNECTION ON SURFACE REACTION

P = 29.2000 ATM
TEMPERATURE EDGE ENTH TEMPERATURE EDGE ENTH
(DEG R) AT I-WALL (DEG R) AT I-WALL
6300.00 1445.39 3000.00 344.00
5400.00 1200.57 2700.00 -37.37
4300.00 781.61 1800.00 -616.44

M-DOT-CHAR/CM M-DOT-CHAR/CM M-DOT-CHAR/CM
TEMP (DEG R) M-DOT-CHAR/CM TEMP (DEG R) M-DOT-CHAR/CM TEMP (DEG R) M-DOT-CHAR/CM
1000.00 -0.001 1000.00 -0.001 1000.00 -0.001
1500.00 -0.001 1500.00 -0.001 1500.00 -0.001
2000.00 -0.001 2000.00 -0.001 2000.00 -0.001
2500.00 -0.001 2500.00 -0.001 2500.00 -0.001
3000.00 -0.001 3000.00 -0.001 3000.00 -0.001
3500.00 -0.001 3500.00 -0.001 3500.00 -0.001
4000.00 -0.001 4000.00 -0.001 4000.00 -0.001
4500.00 -0.001 4500.00 -0.001 4500.00 -0.001
5000.00 -0.001 5000.00 -0.001 5000.00 -0.001
5500.00 -0.001 5500.00 -0.001 5500.00 -0.001
6000.00 -0.001 6000.00 -0.001 6000.00 -0.001
6500.00 -0.001 6500.00 -0.001 6500.00 -0.001
7000.00 -0.001 7000.00 -0.001 7000.00 -0.001
7500.00 -0.001 7500.00 -0.001 7500.00 -0.001
8000.00 -0.001 8000.00 -0.001 8000.00 -0.001
8500.00 -0.001 8500.00 -0.001 8500.00 -0.001
9000.00 -0.001 9000.00 -0.001 9000.00 -0.001
9500.00 -0.001 9500.00 -0.001 9500.00 -0.001
10000.00 -0.001 10000.00 -0.001 10000.00 -0.001

M-DOT-CHAR/CM M-DOT-CHAR/CM M-DOT-CHAR/CM
TEMP (DEG R) M-DOT-CHAR/CM TEMP (DEG R) M-DOT-CHAR/CM TEMP (DEG R) M-DOT-CHAR/CM
1000.00 -0.001 1000.00 -0.001 1000.00 -0.001
1500.00 -0.001 1500.00 -0.001 1500.00 -0.001
2000.00 -0.001 2000.00 -0.001 2000.00 -0.001
2500.00 -0.001 2500.00 -0.001 2500.00 -0.001
3000.00 -0.001 3000.00 -0.001 3000.00 -0.001
3500.00 -0.001 3500.00 -0.001 3500.00 -0.001
4000.00 -0.001 4000.00 -0.001 4000.00 -0.001
4500.00 -0.001 4500.00 -0.001 4500.00 -0.001
5000.00 -0.001 5000.00 -0.001 5000.00 -0.001
5500.00 -0.001 5500.00 -0.001 5500.00 -0.001
6000.00 -0.001 6000.00 -0.001 6000.00 -0.001
6500.00 -0.001 6500.00 -0.001 6500.00 -0.001
7000.00 -0.001 7000.00 -0.001 7000.00 -0.001
7500.00 -0.001 7500.00 -0.001 7500.00 -0.001
8000.00 -0.001 8000.00 -0.001 8000.00 -0.001
8500.00 -0.001 8500.00 -0.001 8500.00 -0.001
9000.00 -0.001 9000.00 -0.001 9000.00 -0.001
9500.00 -0.001 9500.00 -0.001 9500.00 -0.001
10000.00 -0.001 10000.00 -0.001 10000.00 -0.001

TIME	SURF	PROB	SURFACE	M WALL	M CORE	HEAT COEFF	CH/CMO
STEP	ITER	OPIN	RAD (IN)	(BTU/LB)	(BTU/LB)	(LB/50 FT-SEC)	
100	1	1.1000	1.0977	1.0970		.0290	.93291
---RELATION MATS---							
B PRIME	B PRIME	U	M DOT CHAM	M DOT GAS	M CHAM	M GAS	
			(LB/50 FT-SEC)	(LB/50 FT-SEC)	(LB/50 FT-SEC)	(LB/50 FT-SEC)	
.12437	.12352	.035017	.021534	1.567104	1.089242		
---RECESSIONS/RECESSION MATS---							
SURFACE		(IN)	CHAM (IN)	CHAM (IN)	PHYSICIS (IN)		
.239781	.0059297	.025052	.0112474	.060501	.0124473		
---SURFACE ENERGY FLUX TERMS---							
CURRENT RATES (BTU/50 FT SURFACE-SEC)		AND INTEGRATED VALUES (BTU/50 FT)		CHEMICAL		CONDUCTION	
RADIATED		OUT		GENERATION		AWAY	
IN	IN	IN	IN	IN	IN	IN	IN
.15043	.15043	.15043	.15043	.15043	.15043	.15043	.15043
.01104	.01104	.01104	.01104	.01104	.01104	.01104	.01104
---INTERIOR ENERGY TERMS---							
CURRENT RATES (BTU/50 FT SURFACE-SEC)		AND INTEGRATED VALUES (BTU/50 FT)		STORAGE		LOSS AT	
DECOMP		CONVECTION		IN SOLID		HEAT FACE	
IN	IN	IN	IN	IN	IN	IN	IN
.123403	.123403	.123403	.123403	.123403	.123403	.123403	.123403
.013304	.013304	.013304	.013304	.013304	.013304	.013304	.013304
MODE MAT							
1	0	5794.44	76.949	.002862	11	22	946.61
2	0	3354.39	76.949	.002862	12	22	810.04
3	0	3354.39	76.949	.002862	13	22	810.04
4	0	3354.39	76.949	.002862	14	22	810.04
5	0	3354.39	76.949	.002862	15	22	810.04
6	0	3354.39	76.949	.002862	16	22	810.04
7	0	3354.39	76.949	.002862	17	22	810.04
8	0	3354.39	76.949	.002862	18	22	810.04
9	0	3354.39	76.949	.002862	19	22	810.04

TIME	SURF	PROB	SURFACE	M WALL	M CORE	HEAT COEFF	CH/CMO
STEP	ITER	OPIN	RAD (IN)	(BTU/LB)	(BTU/LB)	(LB/50 FT-SEC)	
200	3	1.14002	1.14771	1.14700		.0292	.93851
---RELATION MATS---							
B PRIME	B PRIME	U	M DOT CHAM	M DOT GAS	M CHAM	M GAS	
			(LB/50 FT-SEC)	(LB/50 FT-SEC)	(LB/50 FT-SEC)	(LB/50 FT-SEC)	
.29402	.04451	.027451	.00847	2.698489	1.651891		
---RECESSIONS/RECESSION MATS---							
SURFACE		(IN)	CHAM (IN)	CHAM (IN)	PHYSICIS (IN)		
.3001705	.0044485	.0281906	.0194220	.0740916	.0000126		
---SURFACE ENERGY FLUX TERMS---							
CURRENT RATES (BTU/50 FT SURFACE-SEC)		AND INTEGRATED VALUES (BTU/50 FT)		CHEMICAL		CONDUCTION	
RADIATED		OUT		GENERATION		AWAY	
IN	IN	IN	IN	IN	IN	IN	IN
.157803	.157803	.157803	.157803	.157803	.157803	.157803	.157803
.013705	.013705	.013705	.013705	.013705	.013705	.013705	.013705
---INTERIOR ENERGY TERMS---							
CURRENT RATES (BTU/50 FT SURFACE-SEC)		AND INTEGRATED VALUES (BTU/50 FT)		STORAGE		LOSS AT	
DECOMP		CONVECTION		IN SOLID		HEAT FACE	
IN	IN	IN	IN	IN	IN	IN	IN
.120101	.120101	.120101	.120101	.120101	.120101	.120101	.120101
.013504	.013504	.013504	.013504	.013504	.013504	.013504	.013504
MODE MAT							
1	0	5912.90	76.949	.002862	12	22	1728.25
2	0	5912.90	76.949	.002862	13	22	1148.94
3	0	5912.90	76.949	.002862	14	22	1148.94
4	0	5912.90	76.949	.002862	15	22	1148.94
5	0	5912.90	76.949	.002862	16	22	1148.94
6	0	5912.90	76.949	.002862	17	22	1148.94
7	0	5912.90	76.949	.002862	18	22	1148.94
8	0	5912.90	76.949	.002862	19	22	1148.94
9	0	5912.90	76.949	.002862	20	22	1148.94

MEMORANDUM FOR THE CHIEF, MATERIALS DIVISION, U.S. NAVY
SUBJECT: THERMOCOUPLE TEMPERATURES AND/OR SURFACE TEMPERATURES
MEASURED FROM ORIGINAL SURFACE

TIME	SURF	PROG	SURFACE	90.0000	SECONDS	HEAT COEFF	CH/CHO
STATES	ITCH	OPTN	MOD (IN)	(BTU/LB)	(BTU/LB)	(LB/50 FT-SEC)	
275	3	3	1.5402	1465.18	.00	.00000	
---ABLATION RATES---							
S PRIME	0	M	UOT CHAR	M	DOT GAS	M CHAR	M GAS
.00000	.00000	.00000	(LB/50 FT-SEC)	.00000	.00000	2.658857	1.658183
---RELEASES/RELEASE RATES---							
SURFACE				CHAM	(IN/SEC)	PYROLYSIS (.08)	
.3982171	.0000000			.79489376	.0000140	.7968375 / .0000000	

---SURFACE ENERGY FLUX TERMS---		
CURRENT RATES (BTU/SQ FT SURFACE-SEC)		
AND INTEGRATED VALUES (BTU-DOIO SQ FT)		
CONVECTED	IN	CONDUCTION
		AVAY
	OUT	
		GENERATION
RATE	0.00	0.165+01
	0.00	0.00
TOTAL	0.137-05	0.165+01
	0.00+05	0.257-01
		0.257-01
		0.423+04

---INTERIOR ENERGY TERMS---									
CURRENT RATES (BTU/SQ FT SURFACE-SEC)									
AND INTEGRATED VALUES (BTU/ORIG SQ FT)									
PIROL GAS		DECOMP		CONVECTION		STORAGE		LOSS AT	
PICK UP		ABSORPTION		WITH SOLIDS		IN SOLID		NEAR FACE	
RATE		.9580-04		.3338-01		-.0000		.172-02	
TOTAL		.0260-04		.117-04		-.784-04		.273-04	
MODE	NAT	TEMP	DENSITY	CONDUCTIVITY	MODE	NAT	TEMP	DENSITY	CONDUCTIVITY
1	0	3250-73	1.0000-01	0.0000-01	12	0	2750-41	91.905	0.00374
2	0	3311-48	70.905	0.0000-01	13	0	2698-41	91.905	0.00374
3	0	3325-18	70.905	0.0000-01	14	0	1400-44	103.074	0.00044
4	0	3318-50	70.905	0.0000-01	15	0	481-54	108-708	0.00169
5	0	3165-51	70.916	0.0000-01	16	25	495-61	108-708	0.00108
6	0	3115-41	70.932	0.000718	17	25	543-29	108-708	0.00107
7	0	2860-98	70.945	0.000708	18	7	532-57	486-000	0.000940
8	0	2860-98	91.738	0.000379	19	7	532-07	486-000	0.000940

OUTPUT: DATA

[illegible]

OUTPUT, SAMPLE PROBLEM 2 (CONCLUDED)

CHARGE ANALYSIS AT ABLATIVE THROAT OF A SOLID PROPELLANT ROCKET MOTOR
THROAT SURFACE IS CARRAM PHENOLIC AT A 60 DEGREE LAYUP ANGLE. P=29 ATM
CHAR SWELL AND BURNING RATE CORRECTION ON HEAT TRANS COEF SAMPLE NO. 3

A	20.25	0.0	1.400+04	3.00	1.540+04	1000.0	
4	60.75	32.40	4.400+09	3.00	3.600+04	600.0	
C	94.50	94.50	0.0	0.0	0.0	90000.0	1
	131.12	0.0	120.0	0.5	2.0	5.0	0.3750
	2.0	10.0	0.04	-376.5	0.0	0.0	-0.345
	1.0	1.08	1.4				536.0
	571.0	1330.0					
A	20.250	0.0	0.140+05	3.0	0.154+05	1000.0	
4	60.750	32.40	4.400+10	3.0	0.360+05	600.0	
C	129.00	129.0	0.0	0.0	0.0	90000.0	
			-4807.0	-5200.0	0.0	-0.315	536.0
1	530.0	0.029	1.15				
1	530.0	0.040					
1	530.0	0.040					
1	530.0	0.040					
1	530.0	0.060					
1	530.0	0.100					
1	530.0	0.100					
1	530.0	0.100					
1	530.0	0.150					
1	530.0	0.150					
22	530.0	0.020					
22	530.0	0.040					
22	530.0	0.040					
22	530.0	0.100					
22	530.0	0.100					
22	530.0	0.100					
22	530.0	0.200					
3	530.0	0.250					
3	530.0	0.750					
	0.0	0.0	530.0				
	530.0	0.210	1.000-04	0.630	WX4926 (VIRGIN+60 DEG LAYUP)		
	100.0	0.360	2.130-04	0.630	WX4926 (VIRGIN+60 DEG LAYUP)		
	1140.0	0.360	2.470-04	0.630	WX4926 (VIRGIN+60 DEG LAYUP)		
	1500.0	0.472	2.470-04	0.630	WX4926 (VIRGIN+60 DEG LAYUP)		
	2000.0	0.484	2.470-04	0.630	WX4926 (VIRGIN+60 DEG LAYUP)		
	3000.0	0.493	2.470-04	0.630	WX4926 (VIRGIN+60 DEG LAYUP)		
	4000.0	0.498	2.470-04	0.630	WX4926 (VIRGIN+60 DEG LAYUP)		
	5000.0	0.500	2.470-04	0.630	WX4926 (VIRGIN+60 DEG LAYUP)		
-1	6000.0	0.500	2.470-04	0.630	WX4926 (VIRGIN+60 DEG LAYUP)		
	530.0	0.210	2.470-04	0.630	WX4926 (CHAR +60 DEG LAYUP)		
	1000.0	0.430	2.530-04	0.630	WX4926 (CHAR +60 DEG LAYUP)		
	1500.0	0.472	2.580-04	0.630	WX4926 (CHAR +60 DEG LAYUP)		
	2000.0	0.484	3.240-04	0.630	WX4926 (CHAR +60 DEG LAYUP)		
	3000.0	0.493	7.190-04	0.630	WX4926 (CHAR +60 DEG LAYUP)		
	4000.0	0.498	1.340-03	0.630	WX4926 (CHAR +60 DEG LAYUP)		
	5000.0	0.500	2.000-01	0.630	WX4926 (CHAR +60 DEG LAYUP)		
-1	6000.0	0.500	2.750-01	0.630	WX4926 (CHAR +60 DEG LAYUP)		
	530.0	0.260	0.0001070				
	100.0	0.275	0.000109				
	1140.0	0.310	0.000110				
	1500.0	0.472	0.000110				
	2000.0	0.484	0.000110				
	3000.0	0.493	0.000110				
	4000.0	0.493	0.000110				
-1	5000.0	0.500	0.000110				
	530.0	0.210	0.000314				
	1000.0	0.430	0.000330				
	1500.0	0.472	0.000335				
	2000.0	0.484	0.000356				
	3000.0	0.491	0.000383				
	3500.0	0.495	0.000395				
	4000.0	0.498	0.000427				
-1	5000.0	0.500	0.000587				
3	400.00						
	500.0	0.110	0.00694				
-1	5000.0	0.110	0.00694				
4	0.0						
	0.0	0.0	1.0				
-1	1.0	1.0	0.0				
5	0.001						
	0.0	0.0	1.0				
	0.35	0.0	1.0				
	0.400	0.4	0.0				
	0.00	0.4	0.0				
-1	1.00	1.0	0.0				
1	000.0	1000.0	2700.0	3600.0	4500.0	5400.0	6300.0
	-1707.0	-910.2	145.6	2209.0	3600.0	4696.0	6152.0
	0.0	1947.0	904.0	0.4588	29.2		
	10.0	1947.0	000.0	0.7230	29.2		
	40.000	1947.0	904.0	0.7230	29.2		
	40.000	.05	0.0				
1	170.0	.05	0.0				
	0.607	1.0	0.625	1			0.315

INPUT, SAMPLE PROBLEM 3

AEROTHERM CHAPPING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM

CHM/CBM ANALYSIS AT ABLATIVE THROAT OF A SOLID PROPELLANT ROCKET MOTOR
 THROAT SURFACE IS CARBON PHENOLIC AT A 60 DEGREE LATUP ANGLE. P=29 ATM
 CHAM SRELL AND BURNING RATE CORRECTION ON HEAT TRANS COEF SAMPLE NO. 3

---REACTION KINETIC EQUATION---

DMO/DTIME = GAMMA (BASEXPI-EMT/RHODM(RHOB-RHOB0)/RHODM)*PSIA)
 + GAMMA (B*EXP(-EMT/RHODM(RHOB-RHOB0)/RHODM)*PSIB)
 + (1-GAMMA) (RC*EXP(-EC/T/RHODC(RHOC-RHOC0)/RHODC)*PSIC)

---REACTION KINETIC CONSTANTS---

REACTION RHOD RHOR B PSI E T REAC
 (LB/CU FT) (1/SEC) (DEG R)
 A 20.25 .00 .1400+05 3.00 .1540+05 1000.
 B 60.75 32.40 .4400+10 3.00 .2680+05 600.
 C 94.50 94.50 .0000 .00 .0000 90000.
 RESIN VOLUME FRACTION, GAMMA = .381(MASS FRACTION = .345)

---DECOMPOSING BACK-UP KINETICS---

REACTION RHOD RHOR B PSI E T REAC
 (LB/CU FT) (1/SEC) (DEG R)
 A 20.25 .00 .1400+05 3.00 .1540+05 1000.
 B 60.75 40.50 .4400+10 3.00 .2680+05 600.
 C 129.00 129.00 .0000 .00 .0000 90000.
 RESIN VOLUME FRACTION, GAMMA = .423(MASS FRACTION = .315)

---TIME INCREMENT INFORMATION---

INITIAL TIME (SEC) .000 FINAL TIME (SEC) 120.00
 OUTPUT INTERVAL = .500 SEC FROM INITIAL TIME UNTIL 2.000 SEC
 OUTPUT INTERVAL = 2.000 SEC FROM 2.000 SEC UNTIL 10.000 SEC
 OUTPUT INTERVAL = 5.000 SEC FROM 10.000 SEC UNTIL FINAL TIME
 MAXIMUM TIME STEP =1.00 SECONDS

AEROTHERM CHAPPING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM

PAGE 2
 SAMPLE NO. 3

---NODAL DATA---

MODE NO.	MATL NO.	TEMPERATURE (DEG RANKINE)	RELATIVE THICKNESS (INCHES)	NODAL DEPTH (INCHES)	CONT. DISTANCE (SECT-5-DEG/ATU)
1	1	530.00	.1500+01	.0200	.0000
2	1	530.00	.1100+01	.0400	.0000
3	1	530.00	.1230+01	.0400	.0000
4	1	530.00	.1270+01	.0400	.0000
5	1	530.00	.1320+01	.0400	.0000
6	1	530.00	.1400+01	.1000	.0000
7	1	530.00	.1500+01	.1000	.0000
8	1	530.00	.1600+01	.1000	.0000
9	1	530.00	.1725+01	.1500	.0000
10	1	530.00	.1875+01	.1500	.0000
11	22	530.00	.1960+01	.0200	.0000
12	22	530.00	.1990+01	.0400	.0000
13	22	530.00	.2030+01	.0400	.0000
14	22	530.00	.2100+01	.1000	.0000
15	22	530.00	.2200+01	.1000	.0000
16	22	530.00	.2300+01	.1000	.0000
17	22	530.00	.2450+01	.2000	.0000
18	3	530.00	.2675+01	.2500	.0000
19	3	530.00	.2925+01	.2500	.0000
20	3	530.00	.3150+01	.2500	.0000

*INITIAL INTERNAL RADIUS OF LAST ABLATOR NODE (INCHES) .10400
 MINIMUM THICKNESS OF LAST ABLATOR NODE (INCHES) .0400
 THERE ARE 10 NODELETS ASSIGNED TO EACH ABLATING NODE
 -COEF BTU/FTSQ-SEC-DEG R .0000
 BACK WALL CONVECTION .0000
 BACK WALL EMISSIVITY .0000
 RESERVOIR TEMPERATURE 530.00

---HEAT OF FORMATION OF MATERIAL CONSTITUENTS---

PLASTIC CHAM GAS
 -376.50 .00 .00
 ENTHALPY DATUM TEMPERATURE = 536.000 DEG RANKINE
 DECOMPOSING BACK-UP NO. 1
 PLASTIC CHAM GAS
 -4807.00 -5280.00 .00
 ENTHALPY DATUM TEMPERATURE = 536.000 DEG RANKINE

---MATERIAL THERMAL PROPERTY DATA---

MATERIAL NO. 1 MATERIAL NO. 2 MATERIAL NOS. 3 THROUGH 10
 VIRGIN PLASTIC CHAR BACK-UP
 DECOMPOSING BACK-UP VIRGIN MATERIALS 22.24.26.28.30. CHAR MATERIALS 23.25.27.29.31

AEROTHERM CHAPPING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
PAGE 3
SAMPLE NO. 3

MATERIAL NO. 1	TEMPERATURE	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	DENSITY = 89.302 LB/CU FT	SENSIBLE ENTHALPY	EMISSION
(DEG R)						
500.00		.2100	.0001800		-1.71	.6300
1000.00		.3600	.0002130		75.24	.6300
1500.00		.3600	.0002470		205.84	.6300
2000.00		.4720	.0002470		346.28	.6300
2500.00		.4840	.0002470		585.28	.6300
3000.00		.4930	.0002470		1073.78	.6300
3500.00		.4960	.0002470		1569.28	.6300
4000.00		.5000	.0002470		2068.28	.6300
4500.00		.5000	.0002470		2568.28	.6300

MATERIAL NO. 2	TEMPERATURE	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	DENSITY = 70.884 LB/CU FT	SENSIBLE ENTHALPY	EMISSION
(DEG R)						
500.00		.2100	.0002470		14.48	.6300
1000.00		.3720	.0002470		148.98	.6300
1500.00		.4720	.0002470		372.98	.6300
2000.00		.4930	.0002470		612.98	.6300
2500.00		.4960	.0002470		1101.48	.6300
3000.00		.4980	.0002470		1596.98	.6300
3500.00		.5000	.0002470		2095.48	.6300
4000.00		.5000	.0002470		2595.48	.6300

MATERIAL NO. 22	TEMPERATURE	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	DENSITY = 108.708 LB/CU FT	SENSIBLE ENTHALPY	EMISSION
(DEG R)						
500.00		.2600	.0001070		-1.00	.6300
1000.00		.2750	.0001090		70.82	.6300
1500.00		.3100	.0001100		175.82	.6300
2000.00		.4720	.0001100		308.86	.6300
2500.00		.4840	.0001100		547.86	.6300
3000.00		.4930	.0001100		1036.36	.6300
3500.00		.4960	.0001100		1529.36	.6300
4000.00		.4980	.0001100		2025.86	.6300

MATERIAL NO. 23	TEMPERATURE	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	DENSITY = 91.588 LB/CU FT	SENSIBLE ENTHALPY	EMISSION
(DEG R)						
500.00		.2100	.0003180		-1.92	.6300
1000.00		.3600	.0003300		148.48	.6300
1500.00		.4720	.0003350		372.98	.6300
2000.00		.4840	.0003360		612.98	.6300
2500.00		.4930	.0003430		1101.48	.6300
3000.00		.4950	.0003950		1348.48	.6300
3500.00		.4960	.0004270		1596.73	.6300
4000.00		.5000	.0005820		2995.73	.6300

AEROTHERM CHAPPING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
PAGE 3
SAMPLE NO. 3

MATERIAL NO. 3	TEMPERATURE	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	DENSITY = 886.000 LB/CU FT	SENSIBLE ENTHALPY	EMISSION
(DEG R)						
500.00		.1100	.00089400		-1.100	.375
5000.00		.1100	.00089400		-1.100	.375

TABLES OF OPTIONAL MASS-FRACTION FUNCTIONS FOR THERMAL CONDUCTIVITY
K = F1(X)KP + F2(X)HC

F-FUNCTION TABLE NO. 1 ASSIGNED TO MAIN MATERIAL

X	F1(X)	F2(X)
.0000	.0000	1.0000
.0000	1.0000	.0000

F-FUNCTION TABLE NO. 2 ASSIGNED TO DECOMPOSING BACK-UP NO. 1

X	F1(X)	F2(X)
.0000	.0000	1.0000
.3500	.0000	1.0000
.6000	.0000	1.0000
.9000	.0000	1.0000
1.0000	1.0000	.0000

---RESIN DECOMPOSITION GAS SENSIBLE ENTHALPY---

TEMPERATURE (DEG R)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG R)	ENTHALPY (BTU/LB)
960.00	1800.00	2700.00	3600.00
-1782.00	-930.20	195.00	289.00
5400.00	6300.00		
4896.00	6132.00		

---TIME DEPENDENT BOUNDARY CONDITIONS---

TIME (SEC)	PROB OPTN	RECOVERY ENTHALPY (BTU/LB)	RADIATION HEAT RATE (BTU/SQ FT-SECOND)	HEAT COLFF (BTU/SQ FT-SECOND)	PRESSURE (ATM)	BLOWING REDUCTION PARAMETER
.00	1	1947.00	904.00	.8588	29.20000	.375
10.00	1	1947.00	904.00	.7238	29.20000	.375
60.00	1	1947.00	904.00	.7238	29.20000	.375
TIME (SEC)	PROB OPTN	VIEW FACTOR	RADIATION HEAT RATE (BTU/SQ FT-SECOND)			
60.00	3	.05	.00			
120.00	3	.05	.00			

CH/CHO = PHI/(EXP(PHI)-1.) WHERE PHI = 2.0*BNP*DM DOT/CHO. BRP IN TABLE

OUTPUT, SAMPLE PROBLEM 3 (CONTINUED)

SURFACE TABLES ARE THE SAME AS IN PREVIOUS PROBLEM

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
PAGE 5
SAMPLE NO. 3

---SURFACE EQUILIBRIUM DATA---

RATIO OF MASS TO HEAT TRANSFER COEFFICIENTS = .602
UNEQUAL DIFFUSION EXPONENT = -.000
NOMINAL SURFACE VIEW FACTOR = 1.00 (OPTION 1)
FISSURE MODEL NOT USED FOR GAS TCAMS
HEAT TRANSFER COEFFICIENT MULTIPLIED BY (R INITIAL/H CURRENT) * EX,
WHERE EX = (1.8 - .2N)/(1. - N) AND N IS THE BURNING RATE EXPONENT.
IN THIS PROBLEM N HAS BEEN SET EQUAL TO . .62500
CHAR SWELL = .3100 * CHAR THICKNESS

```
-----OUTPUT-----
TIME SURF PROB SURFACE M WALL M EDGE M WEDGE M CH/CMU
STEP ITER OPTN RAD (IN) (BTU/LB) (BTU/LB) (LB/50 FT-SEC) (LB/50 FT-SEC)
1 0 1 1.1500 .50 1947.00 .8388 .00000

M PRIME H PRIME G M DOT CHAM M DOT GAS M CHAM M GAS
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000

---RECESSIONS/RECESSION RATES---
SURFACE CHAM (IN) / (IN/SEC) PYROLYSIS (.98)
.0000000/ .0000000 .0000000/ .0000000 .0000000

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/50 FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/50 FT)
CONVECTED IN OUT RADIATED CHEMICAL GENERATION CONDUCTION AWAY
RATE .000 .000 .000 .000 .000 .000 .000 .000
TOTAL .000 .000 .000 .000 .000 .000 .000 .000

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/50 FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/50 FT)
PYROL GAS PICK UP DECUMPC CONVECTION STORAGE LOSS AT
RATE .000 .000 .000 .000 .000 .000 .000 .000
TOTAL .000 .000 .000 .000 .000 .000 .000 .000

MODE MAT TEMP DENSITY CONDU/FTU/ MODE MAT TEMP DENSITY CONDU/FTU/
(1000 R) (LB/50 FT) FT SC F) (1000 R) (LB/50 FT) FT SC F)
1 1 530.00 89.362 .000188 11 22 530.00 108.708 .000107
2 1 530.00 89.362 .000188 12 22 530.00 108.708 .000107
3 1 530.00 89.362 .000188 13 22 530.00 108.708 .000107
4 1 530.00 89.362 .000188 14 22 530.00 108.708 .000107
5 1 530.00 89.362 .000188 15 22 530.00 108.708 .000107
6 1 530.00 89.362 .000188 16 22 530.00 108.708 .000107
7 1 530.00 89.362 .000188 17 22 530.00 108.708 .000107
8 1 530.00 89.362 .000188 18 22 530.00 108.708 .000107
9 1 530.00 89.362 .000188 19 3 530.00 486.000 .006940
10 1 530.00 89.362 .000188

SURFACE RECESSION AFTER SWELL (INCHES) .0000
SURFACE RECESSION RATE WITH SWELL (INCHES/SEC) .0000
```

```
-----10.0000 SECONDS-----
TIME SURF PROB SURFACE M WALL M EDGE M WEDGE M CH/CMU
STEP ITER OPTN RAD (IN) (BTU/LB) (BTU/LB) (LB/50 FT-SEC) (LB/50 FT-SEC)
100 3 1 1.2556 .5008 1947.00 .8388 .00001

M PRIME B PRIME G M DOT CHAM M DOT GAS M CHAM M GAS
.29282 .11203 .055043 .034594 .035517 .006503 .006503 .006503

---RECESSIONS/RECESSION RATES---
SURFACE CHAM (IN) / (IN/SEC) PYROLYSIS (.98)
.1028750/ .0003212 .1865787/ .0245823 .3338588/ .0152019

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/50 FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/50 FT)
CONVECTED IN OUT RADIATED CHEMICAL GENERATION CONDUCTION AWAY
RATE .303+03 .570+03 .318+03 .308+04 .715+02 .483+03 .707+04 .707+04
TOTAL .454+04 .574+04 .594+04 .308+04 .715+02 .483+03 .707+04 .707+04

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/50 FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/50 FT)
PYROL GAS PICK UP DECUMPC CONVECTION STORAGE LOSS AT
RATE .200+03 .240+02 .157+03 .101+03 .391+01 .785+01 .785+01 .785+01
TOTAL .250+04 .240+02 .157+03 .101+03 .391+01 .785+01 .785+01 .785+01

MODE MAT TEMP DENSITY CONDU/FTU/ MODE MAT TEMP DENSITY CONDU/FTU/
(1000 R) (LB/50 FT) FT SC F) (1000 R) (LB/50 FT) FT SC F)
1 0 5492.84 71.018 .002496 11 22 530.45 108.708 .000107
2 0 5054.55 .002017 12 22 530.15 108.708 .000107
3 0 4361.92 71.000 .001549 13 22 530.04 108.708 .000107
4 0 3847.41 71.443 .001051 14 22 530.00 108.708 .000107
5 0 2893.99 75.180 .000387 15 22 530.00 108.708 .000107
6 0 1880.66 86.401 .000240 16 22 530.00 108.708 .000107
7 1 659.24 89.362 .000200 17 22 530.00 108.708 .000107
8 1 558.01 89.362 .000191 18 22 530.00 486.000 .006940
9 1 533.62 89.362 .000188 19 1 530.00 486.000 .006940
10 1 530.91 89.362 .000188

SURFACE RECESSION AFTER SWELL (INCHES) .0769
SURFACE RECESSION RATE WITH SWELL (INCHES/SEC) .0046
```

03

1201

22

00-

000

C4A/CRM ANALYSIS AT ABLATIVE THROAT OF A SOLID PROPELLANT ROCKET MOTOR
THROAT SURFACE IS CARBON PHENOLIC AT A 60 DEGREE LAYUP ANGLE, P=29 ATM
FISSURE MODEL APPLIED TO SAMPLE PROBLEM NO. 2

		SAMPLE NO. 2		SAMPLE NO. 4	
A	20.75	0.0	1.400+04	3.00	1.540+04
B	80.75	32.40	4.480+09	3.00	3.680+04
C	94.50	94.50	0.0	0.0	90000.0
101	1.2	0.0	120.0	0.5	2.0
2.0	10.0	0.04	-376.5	0.0	0.0
1.0	1.00	1.4			
531.	1000.				
A	20.250	0.0	0.140+05	3.0	0.154+05
B	60.750	40.50	0.448+10	3.0	0.368+05
C	129.00	129.0	0.0	0.0	90000.0
			-4807.0	-5280.0	0.0
1	530.0	0.020	1.15		-0.315
1	530.0	0.040			536.0
1	530.0	0.040			
1	530.0	0.040			
1	530.0	0.060			
1	530.0	0.100			
1	530.0	0.100			
1	530.0	0.100			
1	530.0	0.150			
1	530.0	0.150			
22	530.0	0.020			
22	530.0	0.040			
22	530.0	0.040			
22	530.0	0.100			
22	530.0	0.100			
22	530.0	0.100			
22	530.0	0.200			
1	530.0	0.250			
3	530.0	0.250			
0.0	0.0	530.0			
530.0	0.210	1.880-04	0.630	MX4926 (VIRGIN+60 DEG LAYUP)	
800.0	0.360	2.130-04	0.630	MX4926 (VIRGIN+60 DEG LAYUP)	
1160.0	0.360	2.470-04	0.630	MX4926 (VIRGIN+60 DEG LAYUP)	
1500.0	0.472	2.470-04	0.630	MX4926 (VIRGIN+60 DEG LAYUP)	
2000.0	0.484	2.470-04	0.630	MX4926 (VIRGIN+60 DEG LAYUP)	
3000.0	0.493	2.470-04	0.630	MX4926 (VIRGIN+60 DEG LAYUP)	
4000.0	0.498	2.470-04	0.630	MX4926 (VIRGIN+60 DEG LAYUP)	
5000.0	0.500	2.470-04	0.630	MX4926 (VIRGIN+60 DEG LAYUP)	
-1 6000.0	0.500	2.470-04	0.630	MX4926 (VIRGIN+60 DEG LAYUP)	
530.0	0.210	2.470-04	0.630	MX4926 (CHAR +60 DEG LAYUP)	
1000.0	0.470	2.530-04	0.630	MX4926 (CHAR +60 DEG LAYUP)	
1500.0	0.472	2.580-04	0.630	MX4926 (CHAR +60 DEG LAYUP)	
2000.0	0.484	3.240-04	0.630	MX4926 (CHAR +60 DEG LAYUP)	
3000.0	0.493	7.190-04	0.630	MX4926 (CHAR +60 DEG LAYUP)	
4000.0	0.498	7.340-04	0.630	MX4926 (CHAR +60 DEG LAYUP)	
5000.0	0.500	7.080-04	0.630	MX4926 (CHAR +60 DEG LAYUP)	
-1 6000.0	0.500	7.750-04	0.630	MX4926 (CHAR +60 DEG LAYUP)	
530.0	0.260	0.0001070			
800.0	0.275	0.0001000			
1160.0	0.310	0.0001110			
1500.0	0.472	0.0001110			
2000.0	0.486	0.0001110			
3000.0	0.493	0.0001110			
4000.0	0.493	0.0001110			
-1 5000.0	0.500	0.0001100			
530.0	0.210	0.000318			
1000.0	0.433	0.000350			
1500.0	0.472	0.000335			
2000.0	0.484	0.000356			
3000.0	0.493	0.000383			
3500.0	0.495	0.000395			
4000.0	0.496	0.000427			
-1 5000.0	0.500	0.000582			
426.00					
500.0	0.110	0.00694			
-1 5000.0	0.110	0.00694			
4	0.0				
-1 1.0	1.0	0.0			
5	0.001				
0.0	0.0	1.0			
0.35	0.0	1.0			
0.600	0.4	0.0			
0.90	0.4	0.0			
+1 1.00	1.0	0.0			
1	900.0	6300.0			
0.0	0.0				
0.0	1947.0	904.0	0.8500	29.2	
10.0	1947.0	904.0	0.7238	29.2	
80.000	1947.0	904.0	0.7238	29.2	
80.000	.05	0.0			
1 120.0	.05	0.0			
0.607	1.0	0.625			
29.20		3500.0	0.0	914.106	914.106-1
29.20		3000.0	0.0	671.985	671.985-1
29.20		2500.0	0.0	434.119	434.119-1
29.20		2000.0	0.0	202.668	202.668-1
29.20		1500.0	0.0	-20.763	-20.763-1
29.20		1000.0	0.0	-231.356	-231.356-1
29.20		500.0	0.0	-405.022	-405.022-1
29.20000	0.00020	0.350003450.80590.	1604.023	1604.023	1 C° 0.
29.20000	0.00020	0.200003158.75570.	992.289	992.289	1 C° 0.

INPUT, SAMPLE PROBLEM 4

29.20000	0.00020	0.150002944.10120.	707.221	707.221	1	C*	0.
29.20000	0.00020	0.100002472.02610.	284.658	284.658	1	C*	0.
29.20000	0.00020	0.092502306.33350.	175.096	175.096	1	C*	0.
29.20000	0.00020	0.087502119.58270.	62.729	62.729	1	C*	0.
29.20000	0.00020	0.085001914.41820.	-56.221	-56.221	1	C*	0.
29.20000	0.00020	0.082501330.25080.	-466.518	-466.518	1	C*	0.
29.20000	0.00020	0.080001299.59080.	-503.670	-503.670	1	C*	0.
29.20000	0.00020	0.060001181.20300.	-698.006	-698.006	1	C*	0.
29.20000	0.00020	0.050001140.60500.	-780.959	-780.959	1	C*	0.
29.20000	0.00020	0.00010 600.47750.	-1384.243	-1384.243	1	C*	0.
29.20000	0.00020	0.00010 500.00000.	-1400.855	-1400.855	1	AL2030	0.
29.20000	0.00010	0.350003450.80590.	1604.023	1604.023	1	C*	0.
29.20000	0.00010	0.200003158.75570.	992.289	992.289	1	C*	0.
29.20000	0.00010	0.150002944.10120.	707.221	707.221	1	C*	0.
29.20000	0.00010	0.100002472.02610.	284.658	284.658	1	C*	0.
29.20000	0.00010	0.092502306.33350.	175.096	175.096	1	C*	0.
29.20000	0.00010	0.087502119.58270.	62.729	62.729	1	C*	0.
29.20000	0.00010	0.085001914.41820.	-56.221	-56.221	1	C*	0.
29.20000	0.00010	0.082501330.25080.	-466.518	-466.518	1	C*	0.
29.20000	0.00010	0.080001299.59080.	-503.670	-503.670	1	C*	0.
29.20000	0.00010	0.060001181.20300.	-698.006	-698.006	1	C*	0.
29.20000	0.00010	0.050001140.60500.	-780.959	-780.959	1	C*	0.
29.20000	0.00010	0.00010 600.47750.	-1384.243	-1384.243	1	C*	0.
29.20000	0.00010	0.00010 500.00000.	-1400.855	-1400.855	0	AL2030	0.

INPUT, SAMPLE PROBLEM 4 (CONCLUDED)

AEROTHERM CHAPPING MATERIAL THERMAL RESPONSE AND ABLATION PHOGRAM
PAGE 1
CMA/CBM ANALYSIS AT ABLATIVE THROAT OF A SOLID PROPELLANT ROCKET MOTOR
THROAT SURFACE IS CANNON PHENOLIC AT A 60 DEGREE LAYUP ANGLE, P=29 ATM
FISSURE MODEL APPLIED TO SAMPLE PROBLEM NO. 2
SAMPLE NO. 4

---REACTION KINETIC EQUATION---
DH0/DTIME = GAMMA (BA*EXP(-E/RT)MHGSA((MH0A-RH0R)/RH00A)*PSIA)
+ GAMMA (BB*EXP(-E/RT)MH0B((MH0B-RH0R)/RH00B)*PSIB)
+ (1-GAMMA) (BC*EXP(-E/RT)MH0C((MH0C-RH0R)/RH00C)*PSIC)

---REACTION KINETIC CONSTANTS---
REACTION MH00 RH0R H PSI E T REAC
(LB/CU FT) (1/SEC) (DEG R) (DEG R)
A 20.25 32.00 .1400*05 3.00 .1540*05 1000.
B 60.75 40.50 .4480*10 3.00 .3680*05 600.
C 94.50 94.50 .0000 .00 .0000 90000.
RESIN VOLUME FRACTION, GAMMA = .381MASS FRACTION = .345

---DECOMPOSING BACK-UP KINETICS---
REACTION RH00 RH0R B PSI E T REAC
(LB/CU FT) (1/SEC) (DEG R) (DEG R)
A 20.25 .00 .1400*05 3.00 .1540*05 1000.
B 60.75 40.50 .4480*10 3.00 .3680*05 600.
C 129.00 .29.00 .0000 .00 .0000 90000.
RESIN VOLUME FRACTION, GAMMA = .423MASS FRACTION = .315

---TIME INCREMENT INFORMATION---
INITIAL TIME (SEC) .000 FINAL TIME (SEC) 120.00
OUTPUT INTERVAL = 5.00 SEC FROM INITIAL TIME UNTIL 2.000 SEC
OUTPUT INTERVAL = 2.000 SEC FROM 2.000 SEC UNTIL 10.000 SEC
OUTPUT INTERVAL = 5.000 SEC FROM 10.000 SEC UNTIL FINAL TIME
MAXIMUM TIME STEP = 1.00 SECONDS

AEROTHERM CHAPPING MATERIAL THERMAL RESPONSE AND ABLATION PHOGRAM
PAGE 2
SAMPLE NO. 4

---NODAL DATA---

NODE NO.	MATL NO.	TEMPERATURE (DEG RANKINE)	RELATIVE THICKNESS (INCHES)	MODAL DEPTH (INCHES)	CONT.-RESISTANCE (SOFT-S-DEG/BTU)
1	1	530.00	.1150*01	.0200	.000000*
2	1	530.00	.1150*01	.0400	.000000
3	1	530.00	.1150*01	.0800	.000000
4	1	530.00	.1270*01	.0400	.000000
5	1	530.00	.1270*01	.0800	.000000
6	1	530.00	.1400*01	.1000	.000000
7	1	530.00	.1500*01	.1000	.000000
8	1	530.00	.1600*01	.1000	.000000
9	1	530.00	.1725*01	.1500	.000000
10	1	530.00	.1875*01	.1500	.000000
11	22	530.00	.1960*01	.0200	.000000
12	22	530.00	.1990*01	.0400	.000000
13	22	530.00	.2030*01	.0400	.000000
14	22	530.00	.2100*01	.1000	.000000
15	22	530.00	.2200*01	.1000	.000000
16	22	530.00	.2300*01	.1000	.000000
17	22	530.00	.2450*01	.2000	.000000
18	3	530.00	.2675*01	.2500	.000000
19	3	530.00	.2925*01	.2500	.000000

*INITIAL INTERNAL RADIUS = 1.150 INCHES
MINIMUM THICKNESS OF ABLATOR MODE THICKNESS = .0400 INCHES
THERE ARE 10 NODES ASSIGNED TO EACH ABLATING NODE

BACK WALL CONVECTION COEF BTU/FTSQ-SEC-DEG R	BACK WALL EMISSIVITY	RESERVOIR TEMPERATURE
.0000	.0000	530.00

---HEAT OF FORMATION OF MATERIAL CONSTITUENTS---
PLASTIC CHAR GAS
-376.50 .00 .00
ENTHALPY DATUM TEMPERATURE = 536.000 DEG RANKINE
DECOMPOSING BACK-UP NO. 1
PLASTIC CHAR GAS
-4807.00 -5280.00 .00
ENTHALPY DATUM TEMPERATURE = 536.000 DEG RANKINE

---MATERIAL THERMAL PROPERTY DATA---
MATERIAL NO. 1 VIRGIN PLASTIC
MATERIAL NO. 2 CHAR
MATERIAL NOS. 3 THROUGH 10 BACK-UP
DECOMPOSING BACK-UP VIRGIN MATERIALS 22,24,26,28,30, CHAR MATERIALS 23,25,27,29,31

MATERIAL NO. 3	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	DENSITY = 485.000 LB/CU FT
(DEG R)			
500.00	.1100	.0069400	
5000.00	.1100	.0069400	

TABLES OF OPTION=1, MASS-FRACTION FUNCTIONS FOR THERMAL CONDUCTIVITY
 $K = F1(X) * KP + F2(X) * KC$

X	F(X)	F2(X)
.0000	.0000	1.0000
.0003	.0000	1.0000
.0006	.0000	1.0000
.0009	.0000	1.0000
.0012	.0000	1.0000
.0015	.0000	1.0000
.0018	.0000	1.0000
.0021	.0000	1.0000
.0024	.0000	1.0000
.0027	.0000	1.0000
.0030	.0000	1.0000
.0033	.0000	1.0000
.0036	.0000	1.0000
.0039	.0000	1.0000
.0042	.0000	1.0000
.0045	.0000	1.0000
.0048	.0000	1.0000
.0051	.0000	1.0000
.0054	.0000	1.0000
.0057	.0000	1.0000
.0060	.0000	1.0000
.0063	.0000	1.0000
.0066	.0000	1.0000
.0069	.0000	1.0000
.0072	.0000	1.0000
.0075	.0000	1.0000
.0078	.0000	1.0000
.0081	.0000	1.0000
.0084	.0000	1.0000
.0087	.0000	1.0000
.0090	.0000	1.0000
.0093	.0000	1.0000
.0096	.0000	1.0000
.0099	.0000	1.0000
.0102	.0000	1.0000
.0105	.0000	1.0000
.0108	.0000	1.0000
.0111	.0000	1.0000
.0114	.0000	1.0000
.0117	.0000	1.0000
.0120	.0000	1.0000
.0123	.0000	1.0000
.0126	.0000	1.0000
.0129	.0000	1.0000
.0132	.0000	1.0000
.0135	.0000	1.0000
.0138	.0000	1.0000
.0141	.0000	1.0000
.0144	.0000	1.0000
.0147	.0000	1.0000
.0150	.0000	1.0000
.0153	.0000	1.0000
.0156	.0000	1.0000
.0159	.0000	1.0000
.0162	.0000	1.0000
.0165	.0000	1.0000
.0168	.0000	1.0000
.0171	.0000	1.0000
.0174	.0000	1.0000
.0177	.0000	1.0000
.0180	.0000	1.0000
.0183	.0000	1.0000
.0186	.0000	1.0000
.0189	.0000	1.0000
.0192	.0000	1.0000
.0195	.0000	1.0000
.0198	.0000	1.0000
.0201	.0000	1.0000
.0204	.0000	1.0000
.0207	.0000	1.0000
.0210	.0000	1.0000
.0213	.0000	1.0000
.0216	.0000	1.0000
.0219	.0000	1.0000
.0222	.0000	1.0000
.0225	.0000	1.0000
.0228	.0000	1.0000
.0231	.0000	1.0000
.0234	.0000	1.0000
.0237	.0000	1.0000
.0240	.0000	1.0000
.0243	.0000	1.0000
.0246	.0000	1.0000
.0249	.0000	1.0000
.0252	.0000	1.0000
.0255	.0000	1.0000
.0258	.0000	1.0000
.0261	.0000	1.0000
.0264	.0000	1.0000
.0267	.0000	1.0000
.0270	.0000	1.0000
.0273	.0000	1.0000
.0276	.0000	1.0000
.0279	.0000	1.0000
.0282	.0000	1.0000
.0285	.0000	1.0000
.0288	.0000	1.0000
.0291	.0000	1.0000
.0294	.0000	1.0000
.0297	.0000	1.0000
.0300	.0000	1.0000

```

---RES-~ DECOMPOSITION GAS SENSIBLE ENTHALPY---
TEMPERATURE (DEG R)      900.00      6300.00
ENTHALPY (BTU/LB)        .00          .00
1.0000      1.0000      .0000

```

---TIME DEPENDENT BOUNDARY CONDITIONS---						
TIME (SEC)	PROG OPTN	RECOVERY ENTHALPY (BTU/LB)	RADIATION HEAT RATE (BTU/SQ FT- SECOND)	HEAT COEFF (LB/50 FT- SECOND)	PRESSURE (ATM)	BLOWING REDUCTION PARAMETER
.00	1	1947.00	904.00	.8588	20.20000	.375
10.00	1	1947.00	904.00	.7238	20.20000	.375
60.00	1	1947.00	904.00	.7238	20.20000	.375
TIME	PH08	VIEW	RADIATION			
(SEC)	OPTN	FACTOR	HEAT RATE (BTU/SQ FT- SECOND)			
60.00	3	.05	.00			
20.00	3	.05	.00			

$$CH/CHO = \mu H / (\exp(\mu H) - 1) \text{ WHERE } \mu H = 2.0 \text{ eV} \cdot \text{nm}^{-1} \cdot \text{nm} \text{ IN TABLE}$$

---SURFACE EQUILIBRIUM DATA---

OUTPUT. SAMPLE PROBLEM 4 (CONTINUED)

AEROTHERM CHIPPING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM

RATIO OF MASS TO HEAT TRANSFER COEFFICIENTS = .002
 UNEQUAL DIFFUSION EXPONENT = .000
 PHYSICAL SURFACE VIEW FACTOR = 1.000 (OPTION 1)
 PHYSICAL MODEL USED FOR SURFACE ENERGY TERMS AND BLOWING CORRECTION
 HEAT TRANSFER COEFFICIENT MULTIPLIED BY INITIAL CURRENT EXPONENT
 HEAT TRANSFER COEFFICIENT MULTIPLIED BY INITIAL RATE EXPONENT
 IN THIS PROBLEM, $h = 2.21 \times 10^{-4}$ AND K IS THE BLOWING RATE EXPONENT
 IN THIS PROBLEM, K IS EQUAL TO .02500
 NO CHAR SWELL CORRECTION ON SURFACE REACTION

P = 29.2000 ATM

TEMPERATURE (DEG M)	EDGE ENTH (BTU/LB)	TEMPERATURE (DEG M)	EDGE ENTH (BTU/LB)	TEMPERATURE (DEG M)	EDGE ENTH (BTU/LB)
6300.00	1645.34	3800.00	364.80	900.00	-729.04
5400.00	1204.57	2700.00	-37.37		
4500.00	781.41	1800.00	-416.44		

M-DOOT-GAS/CM = .0002 PRESSURE = 29.2000 ATM

TEMP (DEG M)	M-DOOT-CHAR/CM	CHEM. PROD (BTU/LB)	SURFACE SPECIES	TEMP (DEG M)	M-DOOT-CHAR/CM	CHEM. PROD (BTU/LB)	SURFACE SPECIES
900.00	.0001	1792.76	C*	3815.45	.0875	428.24	C*
1080.46	.0001	1820.00	C*	4151.40	.0925	428.94	C*
2053.04	.0500	1193.83	C*	4449.65	.1500	376.27	C*
2126.17	.0600	1088.40	C*	5306.58	.1500	38.13	C*
2339.26	.0800	847.37	C*	5685.76	.2500	-308.31	C*
2394.45	.0825	805.03	C*	6211.45	.3500	-1350.00	C*
3445.95	.0850	517.03	C*				

M-DOOT-GAS/CM = .0001

PRESSURE = 29.2000 ATM

TEMP (DEG M)	M-DOOT-CHAR/CM	CHEM. PROD (BTU/LB)	SURFACE SPECIES	TEMP (DEG M)	M-DOOT-CHAR/CM	CHEM. PROD (BTU/LB)	SURFACE SPECIES
900.00	.0001	1792.76	C*	3815.25	.0875	428.24	C*
1080.46	.0001	1820.00	C*	4151.40	.0925	428.94	C*
2053.04	.0500	1193.83	C*	4449.65	.1500	376.27	C*
2126.17	.0600	1088.40	C*	5306.58	.1500	38.13	C*
2339.26	.0800	847.37	C*	5685.76	.2500	-308.31	C*
2394.45	.0825	805.03	C*	6211.45	.3500	-1350.00	C*
3445.95	.0850	517.03	C*				

OUTPUT SAMPLE PROBLEM 4 (CONTINUED)

MODE	HAT	TEMP (DEG R)	DENSITY (LB/CU FT)	CONDUCT (BTU/IN FT SEC)	MODE HAT	TEMP (DEG R)	DENSITY (LB/CU FT)	CONDUCT (BTU/IN FT SEC)
1	0	5753.81	71.048	0.02544	1	22	530.74	108.708
2	0	5250.94	71.079	0.02182	12	22	530.23	108.708
3	0	4158.51	71.298	0.01815	13	22	530.06	108.708
4	0	4158.51	71.298	0.01815	15	22	530.06	108.708
5	0	2945.05	72.570	0.00646	18	22	530.00	108.708
6	0	1095.42	89.362	0.00324	19	22	530.00	108.708
7	1	600.22	89.362	0.00320	17	22	530.00	108.708
8	1	537.54	89.362	0.00191	16	3	530.00	486.000
9	1	537.55	89.362	0.00191	3	3	530.00	486.000
<p>---ABILATION RATES---</p> <p>PRIME G M OOT GAS M DOT GAS M CHAR M GAS M GAS</p> <p>.36617 .1-889 .-57546 .039433 .-57546 .039433 .758908 .576524</p> <p>(LB/IN/SEC) (LB/IN/SEC) (LB/IN/SEC) (LB/IN/SEC) (LB/IN/SEC) (LB/IN/SEC) (LB/IN/SEC) (LB/IN/SEC)</p> <p>---RECESSIONS/RECESSION RATES---</p> <p>SURFACE CHAM (.502) PYROLYSIS (.98)</p> <p>.1218793/.0097448 .144.457/-0.0000381 .3801299/.0174075</p> <p>(IN) (IN) (IN) (IN) (IN) (IN) (IN) (IN)</p> <p>---SURFACE ENERGY FLUX TERMS---</p> <p>CURRENT RATES (BTU/50 FT SURFACE-SEC)</p> <p>AND INTEGRATED VALUES (BTU/IN/50 FT)</p> <p>CONDUCTED RADIATED CONVECTION CHEMICAL</p> <p>IN 76.03 .57403 .034403 .-123.03 CONDUCTION</p> <p>TOTAL .39404 .60104 .33104 .-118.04 .54603 .54603</p> <p>---INTERIOR ENERGY TERMS---</p> <p>CURRENT RATES (BTU/50 FT SURFACE-SEC)</p> <p>AND INTEGRATED VALUES (BTU/IN/50 FT)</p> <p>DECOMP CONVECTION STORAGE LOSS AT</p> <p>PYROL GAS PICK UP ABSORPTION WITH SOLIDS IN SOLIDS NEAR FACE</p> <p>RATE .000 .52402 .16803 .13803 .69101</p> <p>TOTAL .000 .71503 .20904 .26704 .12000</p>								

OUTPUT, SAMPLE PROBLEM 4 (CONCLUDED).

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APPENDIX A
SOME SUGGESTIONS FOR SELECTING NODAL SIZES

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A.1 GENERAL REMARKS

Experience with particular problems will always be the best guide in selecting the sizes of the finite difference nodes within the heated material. Nevertheless, it is possible to set down some very rough guidelines for nodal size which require only a preliminary estimate of the overall character of the solution history rather than detailed experience with closely related problems. The following subsections describe how such preliminary estimates can be turned into moderately useful nodal size assessments.

A.2 NODAL SIZES RELATED TO TIME CONSTANT INFORMATION

Most transient problems have some identifiable time constant which can be used to select a nodal size. This time constant is either the basic resistance times capacitance time constant of the system (usually, of course, the chief resistance is found in the ablating material itself, since the outer heat transfer conductance is very high in most ablation problems) or some time constant associated with a transient boundary condition. The second case is the simpler of the two to visualize: obviously, we want the time constant of the nodal zones to not be significantly larger than the time constant of the boundary condition, θ_{cb} . The time constant of a node is simply

$$\theta_{cn} \approx \frac{\rho C_p \delta A}{kA/\delta} = \frac{\delta^2}{\alpha} \quad (A-1)$$

where ρ , C_p , and k are evaluated at the nodal temperature. Thus, the first nodal size criterion is simply

$$\frac{\delta^2}{\alpha} \approx \theta_{cb} \quad (A-2)$$

or

$$\delta \approx (\alpha \theta_{cb})^{1/2} \quad (A-3)$$

For problems with relatively steady boundary conditions, Equation (A-3) will not yield useful results and one must consider the "natural" time constant of the ablating material, i.e., the first case mentioned above. For a problem with negligible recession and steady boundary conditions, no single set of nodes can be appropriate for the entire problem history. If we let θ_i stand for the time around which interest centers, then the standard similarity solution for the transient temperature in a constant properties slab initially at constant temperature T_i with steady surface temperature T_o impressed at $\theta = 0$ shows that the dimensionless temperature $(T - T_i)/(T_o - T_i)$ has decayed to less than 0.1 at $x/2(\alpha\theta_i)^{1/2} \approx 2$. If we want 10 or so nodes distributed over this region, then

$$\delta = \frac{x}{10} \approx \frac{4(\alpha\theta_i)^{1/2}}{10} = 0.4(\alpha\theta_i)^{1/2} \quad (A-4)$$

which naturally enough is similar to the result of Equation (A-3), even though two different time concepts are involved.

A.3 NODAL SIZES RELATED TO SURFACE RECESSION RATE INFORMATION

If (as is usual) the problem has surface recession \dot{S} , then some additional time step considerations must be made. If \dot{S} and T_w are constant values impressed at time zero for a constant properties slab initially at T_i , the simple analysis shows that the in-depth temperature profile as measured from the heated surface ultimately attains a steady shape

$$\frac{T - T_i}{T_o - T_i} = e^{-\dot{S}x/\alpha} \quad (A-5)$$

This profile decays to 0.1 for $\dot{S}x/\alpha \approx 3$; if we want, say, 10 nodes in this interval then

$$\delta = \frac{x}{10} = \frac{3\alpha}{10\dot{S}} = 0.3\alpha/\dot{S}$$

However, a slightly tighter criterion than this derives from a basic accuracy study of the particular finite difference equations used in CMA. This study, reported in Appendix B of Reference A-1 below, indicated that for good in-depth accuracy one should satisfy the restriction

$$\delta \approx 0.1\alpha/\dot{S} \quad (A-7)$$

A final result of interest may be obtained by noting that the constant \dot{S} , constant T_w problem described here does have a transient beginning and approaches the steady state only as a limit. References A-2 and A-3 show that this limit, as measured by the closeness of approach of q_{cond} to its steady state value is reached to within a few percent at

$$\theta \approx \alpha / \dot{S}^2 \quad (\text{A-8})$$

It is very interesting to observe that if we consider the time given by Equation (A-8) as the "time of interest" and substitute it into the time constant result (A-4), we obtain the result

$$\delta \approx 0.4\alpha / \dot{S} \quad (\text{A-9})$$

which harmonizes rather remarkably with Equation (A-6), derived from steady state profile considerations.

A.4 CONSEQUENCES OF SELECTING INAPPROPRIATE NODE SIZES

The selection of node sizes much smaller than necessary generally merely increases the computing time to far above what could be achieved with more reasonable nodal sizes. In theory, extremely small nodal size could introduce excessive numerical round-off error problems, although this has never been observed in practice with the CMA program.

The choice of too large nodes usually results in a non-obvious lack of accuracy for the entire prediction, especially for the in-depth temperature profile. Important problems should be computed with two different choices of nodal sizes for a check of the accuracy attained. Gross violations of restriction (A-7) sometimes cause drastic and obvious oscillations in the in-depth predictions.

A.5 REMARKS ON NODELETS

As noted in Section 2.1.1 above, the pyrolysis events in the CMA program are computed in a grid of "nodelets" finer than the nodal grid used for the energy calculations. The number of "nodelets" per node may be selected by the user. Experience to date has not been sufficient to lay down any general rules for selecting the number of nodelets per node in various applications. Ten appears sufficient, although many problems seem to do well with fewer. The number of nodelets per node often has an appreciable effect on computation time (see Appendix B below), and for an extensive series of calculations it is worthwhile to minimize this number (by experiment) to reduce costs.

A.6

SUMMARY

The user confronted with an ablation problem outside the range of his prior experience can draw upon several rough guides to select nodal sizes. Locally throughout the material, nodal thicknesses should satisfy the basic thermal profile penetration relation

$$\delta \approx 0.4(\alpha\theta_i)^{1/2} \quad (A-10)$$

where θ_i is a representative real time of principal interest and α is evaluated locally throughout the material. For example, suppose the user is studying nozzle ablation during a 60 second rocket firing and specifies output every 10 seconds. The "real time of interest" to the user is evidently about 10 seconds, since the first output will occur then. The user would set θ_i equal to 10 seconds in Equation (A-10), and select α values for the char for estimating nodal spacing near the surface. Values of α for the virgin plastic would be used for estimating the nodal spacing deeper in the material.

For time varying boundary conditions with a "time constant" or time scale of θ_{cb} ,

$$\delta \approx (\alpha\theta_{cb})^{1/2} \quad (A-11)$$

if this variation is to be "followed" accurately by the in-depth solution. For example, suppose the user is analyzing heat shield ablation during a reentry for which the "heating pulse" rate rises from zero to a maximum in 60 seconds and then decays again in an additional 100 seconds. Speaking in very approximate terms, the "time constant" of such a pulse represents the time required for the pulse to rise about half way from "trough" to peak or to sink roughly half way from peak to trough. This gives time constants of 30 and 50 seconds; the user would naturally select the shorter one for use in Equation (A-11).

Finally, if recession is important, nodal sizes should also satisfy

$$\delta \leq 0.1\alpha/\dot{S} \quad (A-12)$$

to preserve accuracy of the solution.

Most generally users prefer to grade the nodal sizes within the general limits set by these guidelines, beginning with smaller nodes near the heated surface and expanding to rather large nodes (even violating these guidelines) in regions where the thermal pulse does not penetrate, or just begins to penetrate. It is recommended that the user make the first node half the thickness of the second node in all cases, since the program assumes the first node is in fact a half node with only half the usual number of nodelets.

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APPENDIX B
ESTIMATION OF EXECUTION TIME

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ESTIMATION OF EXECUTION TIME

Estimates of computer run time can generally be made by determining the required computation time per time step and multiplying this by the estimated number of time steps needed (equal to problem time divided by time step size). The following sections will discuss this approach. A quicker estimate, adequate for some purposes, may be obtained from the simple empirical statement that most CMA problems consume computer time at a rate of about 20 to 30 percent of the real problem time. This estimate applies to charring problems of about 50 nodes with recession rates less than about 25 mils/sec.

B.1 ROUGH ESTIMATES OF COMPUTER TIME PER TIME STEP

"Typical" problems of the type cited above have been observed to require about 50,000 μ sec to 100,000 μ sec per time step on Univac 1108 and CDC-6600 machines, and about 500,000 μ sec per time step on the IBM 7094 machines.

B.2 REFINED ESTIMATES OF COMPUTER TIME PER TIME STEP

A refined estimate of the computer time required per time step can be obtained from a count of arithmetic operations. The following table of the number of operations in each section of the Charring Material Ablation program provides a useful estimate of execution time as a function of the number of nodes, the number of nodelets per node, and so on.

The input subroutine and all other operations, such as output, not performed each time step, have not been included. Only floating arithmetic is considered.

As an example, with the average operating times for the IBM 7094 (add and subtract = 14 s, multiply = 7 s, divide = 12 s, expf = 188 s, logf = 226 s), this table yields the following floating arithmetic time estimate per time step.

**TABLE OF FLOATING OPERATIONS
FOR ONE TIME STEP**

	Add	Subtract	Multiply	Divide	Expf	Logf
Miscellaneous Nodal Computations, per Node	32	36	64	25	0	0
General Decomposition, per Decomposing Node	22	15	13	3	0	0
Component Decomposition, per Component for each Decomposing Nodelet	1	3	4	3	3	2
Surface Calculations, per Iteration	25	39	50	10	1	0

$$T = [(1136 \cdot I + 645)J \cdot F + 1700]N + K(1534) \text{ } \mu\text{sec/step}$$

where

T = execution time for a single time step (μsec)

I = number of decomposing components in the material

J = number of nodelets per node

F = fraction of nodes decomposing

N = total number of nodes

K = number of iterations in surface energy balance

In this equation, F should be an average value for the fraction of nodes actively decomposing during the problem (usually between 1/3 and 1/2). A study of numerous problems reveals that K averages very close to 3.

The resulting total time must be multiplied by a factor to account for "administrative" arithmetic such as DO loop indexing. Experience with this program on the 7094 suggests a factor between 1.4 and 1.5

B.3 DETERMINATION OF NUMBER OF TIME STEPS REQUIRED

To estimate total execution time, the time per time step T may be multiplied by the total number of time steps, a number approximately determined by the user in the choice of the maximum time step allowed (see Section 3.1.3

above). For some problems, however, a built-in limit based on the recession rate turns out to be smaller. This limit prevents the time step Δt from allowing more than the thickness of one nodelet to ablate during a time step; thus

$$\Delta t \leq \min(2\delta_1, \delta_2, \delta_3, \delta_4, \dots, \delta_{NL_{\min}}) / \dot{S}$$

where the δ 's are the nodal thickness in the main charring material and $\delta_{NL_{\min}}$ is the minimum allowed thickness for the last ablating node (Section 3.1.3, p. 3-3 above).

B.4 OTHER CONSIDERATIONS

Additional machine time will be consumed by input and loading operations, overlay or special tape handling (if necessary), and output operations, the details of which are peculiar to individual computing facilities.

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13. ABSTRACT This two-volume report describes a Fortran-IV computer code which computes the transient thermal and ablation response of a charring insulation material structure. The program is for one-dimensional bodies, but can treat a variety of shapes, including planes, cylinders, spheres, and more general thermal "stream tube" bodies. The program can treat complex systems including a main ablating material, several charring back-up materials, and a multiple non-charring material back-up structure.			

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